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Dear Professor Carlo Alberto Nucci, Editor-in-Chief of Electric Power Systems Research,

We wish to submit an original research article entitled "**Dynamic Under Voltage Load Shedding Scheme Considering Composite Load Modeling**" for consideration by Electric Power Systems Research. We confirm that this work is original and has not been published elsewhere, nor is currently under consideration for publication elsewhere.

In this paper, we report on a novel scheme for an under voltage load shedding (UVLS) in an electric power system based on sensitivity of dynamic voltage curves to mitigate voltage collapse. Furthermore, detailed static and dynamic load modeling are considered, and load compositions are included for a more realistic, reliable and effective UVLS design, which has not been considered in other works. This is important because in the modern power system nowadays with substantial quantity of dynamic motor loads, with only static load model in time domain simulation is inadequate to evaluate the process of voltage collapse. As the power system becomes profoundly stressed and works at its boundaries with reduced capacity and stability margins, a more precisely representation of load characteristic becomes more vital. To plan a robust UVLS scheme, it is essential to precisely represent the load model inclusive of induction motors. Moreover, the proper load modeling will give significant impact on the accuracy of the simulation results. Then, this work developed new index named dynamic voltage-active power sensitivity (DVPS). The DVPS is calculated in all load buses to give information about bus that has a predominant influence on improving system voltage stability through load shedding. We believe that this manuscript is appropriate for publication by Electric Power Systems Research because it reports innovation in under voltage load shedding scheme to maintain power system stability when the power system is being disturbed, which this research covers power system elements modelling, UVLS design, analysis and its implementation in modern electrical power.

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Thank you for your consideration of this manuscript.

Sincerely yours,

Ardiaty Arief, Ph.D.

## HIGHLIGHTS

- A novel under voltage load shedding (UVLS) scheme is developed using dynamic voltage stability analysis.
- Detailed static and dynamic load modeling are considered, and load compositions are included for a more realistic, reliable and effective UVLS design.
- A new formulation of dynamic voltage active power sensitivity (DVPS) is formulated to determine location and amount of load shedding.
- The proposed method are compared with the utility’s scheme.

# Dynamic Under Voltage Load Shedding Scheme Considering Composite Load Modeling

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*Abstract*—This manuscript recommends an under voltage load shedding scheme based on the sensitivity of dynamic voltage curves to mitigate voltage collapse in highly stressed power systems. The developed method can be used to determine the minimum amount and proper locations of load curtailment by considering power system dynamics including dynamic load modeling. The selected Indonesian regional system has a large number of dynamic loads in form of air conditioning and water pump loads whose dynamics contribute considerably to the complexity of the power system stability. Loss of the transmission line in the system caused by the impact of the composite load after major disturbance is studied. The proposed scheme involves an iterative procedure based on the sensitivity analysis of dynamic voltage curve to solve the problem of load shedding. Furthermore, this work developed new index named dynamic voltage-active power sensitivity (DVPS). The DVPS is calculated in all load buses to give information about bus that has a predominant influence on improving system voltage stability through load shedding. Dynamic simulations are carried out with an Indonesian power system, the South Sulawesi interconnection power system with the proposed load shedding scheme. The results of this work show a noteworthy improvement in the magnitude of the voltage level as well as the voltage stability margin.

*Keywords*—dynamic load modeling, dynamic voltage curve sensitivity, under voltage load shedding, voltage stability, voltage stability margin.

**Nomenclature**

| | |
|---|---|
| DVPS | dynamic voltage-active power sensitivity |
| UVLS | under voltage load shedding |
| VSM | voltage stability margin |
| $E_d^{'}$ | *d*-axis stator transient voltage related to rotor transient flux component |
| $E_q^{'}$ | *q*-axis stator transient voltage related to rotor transient flux component |
| $E_f^{*}$ | field voltage |
| $H$ | inertia constant |
| $I_d$ | *d*-axis element of stator current |
| $I_q$ | *q*-axis element of stator current |
| $T_{do}^{'}$ | *d*-axis transient time constant |
| $T_{qo}^{'}$ | *q*-axis transient time constant |
| $T_{do}^{''}$ | *d*-axis subtransient time constant |
| $T_{qo}^{''}$ | *q*-axis subtransient time constant |
| $T_{FW}^{*}$ | extra damping torque in comparison to rotor speed |
| $T_M$ | mechanical torque |
| $X_d^{'}$ | *d*-axis transient reactance |
| $X_q^{'}$ | *q*-axis transient reactance |
| $X_d^{''}$ | *d*-axis subtransient reactance |
| $X_q^{''}$ | *q*-axis subtransient reactance |
| $X_{ls}$ | armature leakage reactance |
| $\delta$ | generator rotor power angle |
| $\psi_d$ | subtransient EMFs as a result of *d*-axis damper flux linkage |
| $\psi_q$ | subtransient EMFs as a result of *q*-axis damper flux linkage |
| $\omega$ | generator rotor angular speed |
| $\omega_s$ | generator synchronous rotor speed ($2\pi f$) |
| $P_{Li}$ | active load on the bus *i* |
| $Q_{Li}$ | reactive load on the bus *i* |
| $P_{Li}^{0}$ | active load according to the initial bus voltage |
| $Q_{Li}^{0}$ | reactive load according to the initial bus voltage |
| $\alpha_P$ | constant impedance element of the active load |
| $\alpha_Q$ | constant impedance element of the reactive load |
| $\beta_P$ | constant current element of the active load |

| | |
|---|---|
| $\beta_Q$ | constant current element of the reactive load |
| $\gamma_P$ | constant power element of the active load |
| $\gamma_Q$ | constant power element of the reactive load |
| $V_i$ | actual operating voltage at bus *i* |
| $P_s(V)$ | steady state active power load as function of voltage |
| $Q_s(V)$ | steady state reactive power load as function of voltage |
| $P_t(V)$ | transient active power load as function of voltage |
| $Q_t(V)$ | transient reactive power load as function of voltage |
| $P_d$ | instantaneous active power |
| $Q_d$ | instantaneous reactive power |
| $T_p$ | active power time constant |
| $T_q$ | reactive power time constant |
| $x_p$ | active power load state variable |
| $x_q$ | reactive power load state variable |
| $P_{shed_j}$ | load shedding quantity on bus *j* |
| $n_k$ | critical buses number |
| $t_k$ | instantaneous time |
| $t_s$ | number of instantaneous time |

## 1. Introduction

### *1.1 Background and Motivations*

Since the last century, the stability of the electric power system has been believed as an important precondition for a secure and stable operation of the power system [1]. As the power system expands to a more complex and highly stressed system, with increasing number of interconnections, renewable energy resources integration, direct current transmission system as well as electricity market, the problem of voltage stability also becomes more crucial, since the stability characteristics of the system becomes more complicated than before [2]. During the power system scheduling and operation, the problem of voltage stability has been a major interest, due to the considerable amount of system failures caused by voltage instability which is usually caused by a power outage or a sudden increase in load. There are two common defense measures to prevent voltage instability, namely preventive measures and corrective measures. Preventive measures are taken in a pre-contingency state to improve the margin of voltage security, while corrective measures are usually carried out during post-interference configurations to reinstate system stability. Among the various precautions that can be implemented to preclude voltage instability, load shedding or load curtailment becomes more acceptable as an inexpensive and reliable corrective measure. Nevertheless, the load shedding must be the final remedial defense when no other alternative is available to prevent the possibility of a voltage collapse. UVLS plays an important role in power system control and stability when the system is experiencing major disruptions. Various research has confirmed that load shedding is an effective counter-measure action against frequency or voltage instability. Load shedding is a partial cost-effective remedy to the challenges of voltage and frequency stability. It has been utilized for a long time as a last resort to avoid breakdowns to the main power system triggered by low frequencies or under voltage relays [3].

### *1.2 State-of-the-art of Power System Under Voltage Load Shedding*

Various research had been conducted to investigate preventive and corrective actions to preclude instability using voltage stability analysis, which is an imperative instrument for predicting probable instability and generally can be categorized into: static, quasi-static and dynamic voltage stability analysis. In the literature, numerous methods have been utilized to design effectual UVLS schemes. Most of them use static or dynamic voltage stability analysis. This section will provide an overview of existing UVLS methods. The authors in [4] developed an optimization model with relaxation restrictions to compute minimal load shedding. A load shedding based on modal participation factors was proposed in [5] to identify load shedding location. The multistage method for deciding the location and minimum amount of load curtailment was presented in [6]. The author in [7] developed UVLS based on integer value modeling and presented the interruption penalty factor for feeders and the participation penalty factor for buses to minimize the total curtailment of the load. A load shedding was designed by using Particle swarm optimization (PSO) in [8]. Teaching learning based optimization (TLBO) was implemented in [9] for load shedding and the locations for load shedding were determined by using the severity index sensitivity. The work in [10] formulated an improved risk-based AC security-constrained optimal power flow (RB-SCOPF) for load shedding amount. Another OPF based UVLS to determine the amount, place, degree and timing of load shedding to maintain a predetermined voltage stability margin was proposed by [11] and Linear optimization-based optimal power flow (LP-OPF) for load shedding was suggested by [12]. The work in [13] established load shedding requirements of the extended equal area criterion (EEAC). The authors in [14] recommended a technique for determining load shedding location by taking into consideration multi-contingencies by tracking the stability index and for computing load shedding amount by using a modified fuzzy logic system. Hybrid Imperialist Competitive Algorithm-Pattern Search (HICA-PS) was employed for load shedding in [15]. In paper [16], the authors presented a load shedding scheme by using eigenvalue of the Jacobian matrix to determine load shedding location and using Genetic Algorithm (GA) and Neural Network (NN) to compute load shedding amount. However, these UVLS schemes were developed based on static voltage analysis approach. The drawback of the static voltage analysis technique is that it cannot justify the dynamic character of the occurrences of voltage collapse. The static and quasi-static voltage stability analysis are based on the power flow snapshots and these methods do not take into consideration the dynamic modeling of the system. On the other hand, time domain simulations hold an important role in assessing the voltage collapse phenomena mechanism.

The studies in [17-20][23] investigated UVLS schemes based on time domain simulations. A UVSL based on adaptive model predictive control (MPC) was developed by [17]. Remedial action scheme (RAS) was created in [18] where candidates load shedding location were ranked according to their categories and influences on the system stability and enactment. The authors in [19] analyzed the impacts of grid behavior with various UVLS schemes. Study in [20] presented a wide area voltage stability index based load shedding scheme and used modified Discrete Imperialistic Competition Algorithm (DICA) to solve the load shedding. Even though these studies proposed UVLS based on time domain simulations, yet in these works, detailed load modeling (static and dynamic load model) are not considered. Nevertheless, load modeling is important and holds a vital part in the assessment of dynamic voltage stability as well as design of UVLS, hence proper modeling of the load will give significant impact on the accuracy of the simulation results.

### *1.3 Contributions of This Paper*

Based on the discussion above, there were a considerable number of research works that have investigated and proposed different UVLS schemes. However, these studies have no consideration for detailed load modeling and do not fully take into account the system dynamic modeling particularly from the majority proportion of induction motor loads in a power system.

In the modern power system with substantial quantity of air conditioning loads, with only static load model in time domain simulation is inadequate to evaluate the process of voltage collapse. Especially in Indonesia, several systems are featured with significant air conditioning and pumping loads. As the power system becomes profoundly stressed and works at its boundaries with reduced capacity and stability margins, a more precisely representation of load characteristic becomes more vital. Instability in a power system with considerably large quantity of dynamic motor loads can result in slow voltage improvement or rapid voltage drop [21]. The deficiency of dynamic load modeling in the time domain simulation is assumed to be the main reason for the inconsistencies between real measurements and simulation outcomes. Motors have troubles to reaccelerate after main interruptions and can distress voltage profile improvement [22]. Induction motors may stall and draw high currents and result in an increase in voltage drop in some areas in the system. To plan a robust UVLS scheme, it is essential to precisely represent the load model inclusive of induction motors. Moreover, the proper load modeling will give significant impact on the accuracy of the simulation results. Therefore, for financial reasons, hence it is crucial to determine a technique for optimum and more precise load shedding that incorporates dynamic induction motor models.

In this paper, a new analytic and systematic method is suggested to design a strategic under voltage load shedding scheme which incorporates dynamic voltage sensitivity analysis as an approach for computing the amount and location of load curtailment in a power system. The developed method comprises of an iterative procedure that calculates the bus dynamic voltage sensitivities in regard to the amount of load shedding. At each stage, the load shedding quantity is set to a small amount of about 1% of the total load. Additionally, a new formulation, namely dynamic voltage-active power sensitivity (DVPS) is created based on dynamic voltage sensitivities to decide the location of load shedding. Furthermore, the proposed UVLS scheme is evaluated based on the voltage stability margin.

Therefore, to fulfill this imperative research gap, this work aims to deliver these novel contributions:

i. A new UVLS scheme is developed using dynamic voltage stability analysis;
ii. Detailed static and dynamic load modeling are considered, and load compositions are included for a more realistic, reliable and effective UVLS design; and
iii. A new formulation of dynamic voltage active power sensitivity (DVPS) is formulated to determine location and amount of load shedding.

The UVLS method developed in this paper involves multistage or iterative solutions. The main reason for this iterative process is to minimize the load shedding amount by analyzing its dynamic sensitivity with a small amount of load shedding for every iteration until the system is stable hence the optimal or minimum amount for load shedding can be obtained.

The remainder of this paper is organized as follow: Section II provides explaination about power system modeling for the UVLS design. Section III outlines the proposed methodology: the dynamic voltage sensitivities enhanced UVLS scheme. Section IV specifically gives information about the South Sulawesi system in Indonesia. Section V provides the results and analysis then Section VI concludes the research key outcomes . This work results are expected to deliver a better setting of UVLS to deal the possibility of voltage collapse occurrence, particularly in the South Sulawesi power system.

## 2. Power Systems Modeling for Under Voltage Load Shedding Studies

The first step of dynamic voltage stability assessment is to have reliable power system model. This includes key elements of a power system, i.e. generators, network and loads for both steady state and dynamic. This following section describes the system modeling for the proposed UVLS scheme.

### *2.1 Synchronous Generator Modeling*

The synchronous generator model employed in this work is the detailed 6th order synchronous machine model. The 6th order synchronous machine model considers four windings with the existence of a field circuit and supplementary circuit by the *d*-axis and two further circuits through the *q*-axis. Nevertheless, the network and stator transients in the 6th order model are ignored. The dynamics generated by these transients are negligible and would give slightly conservative results, which are more suitable for dynamic analysis, predominantly for fast screening to identify and recognize all critical and unstable consequences [24]. In dynamic voltage stability, the differential equations overseeing the subtransient behaviour of the 6th order synchronous machines are given by the following equations [25],

$$T'_{do}\frac{dE'_q}{dt} = -E'_q - \left(X_d - X'_d\right)\left[I_d - \left(\frac{X'_d - X''_d}{\left(X'_d - X_{ls}\right)^2}\right)\left\{\psi_d + \left(X'_d - X_{ls}\right)I_d + E'_q\right\}\right] + E_f^* \tag{1}$$

$$T''_{do}\frac{d\psi_d}{dt} = -\psi_d + E'_q - \left(X'_d - X_{ls}\right)I_d \tag{2}$$

$$T'_{qo}\frac{dE'_d}{dt} = -E'_d + \left(X_q - X'_q\right)\left[I_q - \left(\frac{X'_q - X''_q}{\left(X'_q - X_{ls}\right)^2}\right)\left\{\psi_q + \left(X'_q - X_{ls}\right)I_q + E'_d\right\}\right] \tag{3}$$

$$T''_{qo}\frac{d\psi_q}{dt} = -\psi_q + E'_d - \left(X'_q - X_{ls}\right)I_q \tag{4}$$

$$\frac{d\delta}{dt} = \omega - \omega_s \tag{5}$$

$$\frac{2H}{\omega_s}\frac{d\omega}{dt} = T_M - \left(\frac{X_d'' - X_{ls}}{X_d' - X_{ls}}\right)E_q' I_q - \left(\frac{X_d' - X_d''}{X_d' - X_{ls}}\right)\psi_d I_q - \left(\frac{X_q'' - X_{ls}}{X_q' - X_{ls}}\right)E_d' I_d + \left(\frac{X_q' - X_q''}{X_q' - X_{ls}}\right)\psi_q I_d - \left(X_q'' - X_d''\right)I_d I_q - T_{FW}^* \tag{6}$$

### 2.2 Load Modeling

Load modeling is crucial and one of the most important elements in the dynamic voltage stability analysis including in the UVLS design. In this study, the load on each bus is demonstrated as a composite load model which is a combination of static and dynamic load components. Section V elaborates further details of the load configuration in this work. Fig. 1 shows the equivalent circuit of the composite load model, where *Z* is constant impedances; *I* is constant currents; *P* is constant powers; $X_m$ is the magnetization reactance; $X_s$ is the stator leakage reactance; $X_r$ is the rotor leakage resistance; $R_s$ is the stator resistance; $R_r$ is the rotor resistance; and *s* is the induction motor slip.

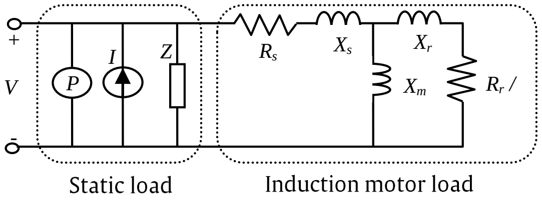

Fig. 1 Schematic circuit of the composite load model [26]

#### 2.2.1 Static Load Modeling

In general, loads are contingent on the voltage of a bus. Static load voltage reliance can be stated through exponential or polynomial or equations. Static ZIP load modeling is commonly expressed as a voltage magnitude function on a particular bus connected to the load as [27],

$$P_{Li}(V_i) = P_{Li}^0\left[\alpha_P\left(\frac{V_i}{V_0}\right)^2 + \beta_P\left(\frac{V_i}{V_0}\right) + \gamma_P\right] \tag{7}$$

$$Q_{Li}(V_i) = Q_{Li}^0\left[\alpha_Q\left(\frac{V_i}{V_0}\right)^2 + \beta_Q\left(\frac{V_i}{V_0}\right) + \gamma_Q\right] \tag{8}$$

### *2.2.2 Dynamic Load Modeling*

Dynamic load modeling is essential for UVLS strategy, since induction motors will slow down substantially when their terminal voltage declines because of short circuits. The common models for induction motor type dynamic loads are [28],

$$T_p\frac{dP_d}{dt} + V^{\alpha_t}P_d = V^{\alpha_t}P_s(V) + \alpha_t T_p\frac{P_d}{V}\frac{dV}{dt} \tag{9}$$

$$T_q\frac{dQ_d}{dt} + V^{\beta_t}Q_d = V^{\beta_t}Q_s(V) + \beta_t T_q\frac{Q_d}{V}\frac{dV}{dt} \tag{10}$$

where $\alpha_t$, $\alpha_s$, $\beta_t$, $\beta_s$, $P_1$ and $Q_1$ are constants independent of load busbar voltage $V$.

## 3. Dynamic Voltage Sensitivities Enhanced UVLS Scheme

### *3.1 Dynamic Voltage Stability Analysis*

Dynamic voltage stability analysis is a constructive method for investigating the state of a specific voltage collapse and examining the coordination of time-dependent time-control measures and system protection. Analysis of dynamic voltage stability employs time domain simulation to present an explanation of differential equations of nonlinear systems. Dynamic voltage stability analysis is very important to assess system performance, to control system design and to develop methods to prevent voltage collapse. Proper power system modeling and time domain simulations can portray time events and their chronology until the voltage collapse final phase.

### *3.2 Dynamic Voltage Active Power Sensitivity Analysis*

The dynamic voltage active power sensitivity analysis is developed based on the dynamic voltage curve sensitivity analysis which is a method based on the linearization of the system that surrounds a particular tracking and utilizes time domain simulations, which differs from the P-V curves that are usually used in steady-state voltage stability analysis. This process calculates the dynamics sensitivity associated to constraints. Dynamic sensitivity is able to enumerate fluctuations in system variables in correlation with respect to rapid alterations in system parameters and initial conditions. Computation of these sensitivities based analysis can be found in [29] and discussed briefly below for completeness.

A power system model can be demonstrated by the following differential-algebraic equations (DAEs) for a systematic voltage stability analysis:

$$\dot{x} = f(x, y; \alpha) \tag{11}$$

$$0 = g(x, y; \alpha) \tag{12}$$

where $x$ represents dynamic variables vector; $y$ denotes algebraic variables vector such as voltage magnitudes and angles of the load bus; and $\alpha$ symbolizes system constraints/parameters.

The paths of (11) and (12) demonstrate the dynamic variables $x$ and algebraic variables $y$ performances, where movements of variables $x$ and $y$ can be expressed as,

$$x(t) = \varphi_x(x_0, t, \alpha) \tag{13}$$

$$y(t) = \varphi_y(y_0, t, \alpha) \tag{14}$$

The Taylor series expansion is implemented in the above equations to acquire the movement sensitivities of $\varphi_x$ and $\varphi_y$ to the original situations and parameter changes, hence

$$\Delta x(t) = \Delta\varphi_x(x_0, t, \alpha) = \frac{\partial \varphi_x(x_0, t, \alpha)}{\partial \alpha}\Delta\alpha = \frac{\partial x(t)}{\partial \alpha}\Delta\alpha \cong x_\alpha(t)\Delta\alpha \tag{15}$$

$$\Delta y(t) = \Delta\varphi_y(y_0, t, \alpha) = \frac{\partial \varphi_y(y_0, t, \alpha)}{\partial \alpha}\Delta\alpha = \frac{\partial y(t)}{\partial \alpha}\Delta\alpha \cong y_\alpha(t)\Delta\alpha \tag{16}$$

The sensitivities of $x_\alpha$ and $y_\alpha$ is computed by using approximate numeric method, consequently

$$x_\alpha = \frac{\partial x}{\partial \alpha} = \frac{\Delta x}{\Delta \alpha} \approx \frac{\varphi_x(x_0, t, \alpha + \Delta\alpha) - \varphi_x(x_0, t, \alpha)}{\Delta \alpha} \qquad (17)$$

$$y_\alpha = \frac{\partial y}{\partial \alpha} = \frac{\Delta y}{\Delta \alpha} \approx \frac{\varphi_y(y_0, t, \alpha + \Delta\alpha) - \varphi_y(y_0, t, \alpha)}{\Delta \alpha} \qquad (18)$$

### *3.3 The dynamic voltage-active power sensitivity (DVPS) Formulation and Research Algorithm*

The dynamic sensitivities of (16) and (18) are modified to encounter the main intention of this research. Although Q-V curve is normally used for voltage stability assessment, however, in order to have more straight forward indicator for direct load shedding decision making, it is more convenient to have an indicator associated with active power (P). Therefore, we proposed the UVLS design by assessing the degree of change in voltage magnitude in regard to the degree of change in active power. The variable $y$ represents the bus voltage magnitude and the load shedding amount are denoted by $\alpha$, then the bus voltage variation sensitivities after load shedding on a particular bus are calculated as

$$\Delta V(t) = \Delta\varphi_V(V_0, t, P) = \frac{\partial \varphi_V(V_0, t, P)}{\partial P}\Delta P = \frac{\partial V(t)}{\partial P}\Delta P \cong V_P(t)\Delta P \qquad (19)$$

$$\varphi V_P = \frac{\partial V}{\partial P} = \frac{\Delta V}{\Delta P} \approx \frac{\varphi_V(V_0, t, P + \Delta P) - \varphi_V(V_0, t, P)}{\Delta P} \qquad (20)$$

The dynamic sensitivities are executed to obtain the location of load shedding as well. A dynamic voltage-active power sensitivity (DVPS) is formulated to provide information about the participation of bus *j* after load shedding on bus *j* with predefined amount to the enhancement of the system voltage stability. The premeditated sensitivity is $[\partial V_i / \partial P_j]$, which notifies the degree of voltage magnitude variations on bus *i* in regard to the changes in load shedding amount on bus *j*. The DVPS on bus *j* is calculated by curtailing active power on bus *j* by a small quantity then evaluates its effect on all critical buses voltage magnitudes along time domain, hence the DVPS is formulated as,

$$DVPS_j = \sum_{i=1}^{n_k} \left[ \sum_{t=0}^{t_s} \left[ \frac{\partial V_i}{\partial P_j} \right]_{t=t_k} \right] \tag{21}$$

$$\partial P_j = \Delta P_j = P_{shed_j}$$

The bus with the highest DVPS has the predominant influence in improving the system voltage stability on the critical buses based on time domain analysis, therefore this bus is chosen as a candidate for load shedding location. For better understanding, the stages for determination of the amount and location of load shedding are illustrated through the flowchart in Fig. 3 whereas the computational procedures are explained in detail below:

*Step 1* Calculation of the load shedding quantity. In this research, the load shedding quantity is arranged at 1 % of the total load for each iteration.

*Step 2* Determination of a predefined set of contingencies, then select a fault.

*Step 3* Execution of dynamic voltage stability analysis or time domain simulation analysis to examine the voltage behavior for all buses in case of unforeseen circumstances. In this stage, the post-fault voltage recovery on all buses are checked whether they are within the stability limit. If so, the process terminates. Otherwise, it indicates that the system needs load shedding to avoid possible voltage collapse, then go to *Step 4*.

*Step 4* Identification of critical buses and regions. The critical region is the region where neighboring buses experience voltage drop below the stability limit and they have similar voltage drop trajectory.

*Step 5* Calculation of DVPS using Eq. (21) to evaluate the influence of each load bus in the voltage stability recovery of the buses within the critical areas with load shedding quantity of 1% of the total load. The bus with the highest DVPS means that this bus is the most sensitive bus therefore it has the main influence on increasing the voltage magnitude with a small amount of load shedding. The location of load shedding is determined based on the highest DVPS value.

*Step 6* Application of load shedding on the designated bus with the highest DVPS.

*Step 7* Execution of dynamic voltage stability analysis to assess system operation after load shedding. At this point, further examinations are carried out to identify whether the post fault voltage recovery performance on all load buses after load shedding satisfy the voltage stability constraints. If yes, the workflow proceeds to *Step 8* to conclude the process and write the results. Else, it indicates more load shedding, hence the framework switches to *Step 5.*

*Step 8* Completion of dynamic UVLS scheme process, write the results and stop the process.

### *3.4 Stability Constraints, Optimization Objective and Voltage Stability Margin*

In order to meet the voltage stability criteria, the following voltage stability constraints are used:

$$0.9 \leq V_{(t_{k+N})} \leq 1.1 \tag{22}$$

Furthermore, the optimization objective of the dynamic curve sensitivity UVLS is to determine minimum quantity of load shedding to ensure voltage constraints are met, then

$$\min \sum_{j=i}^{m} P_{shed_j} \tag{23}$$

where $m$ is the number of load shedding location.

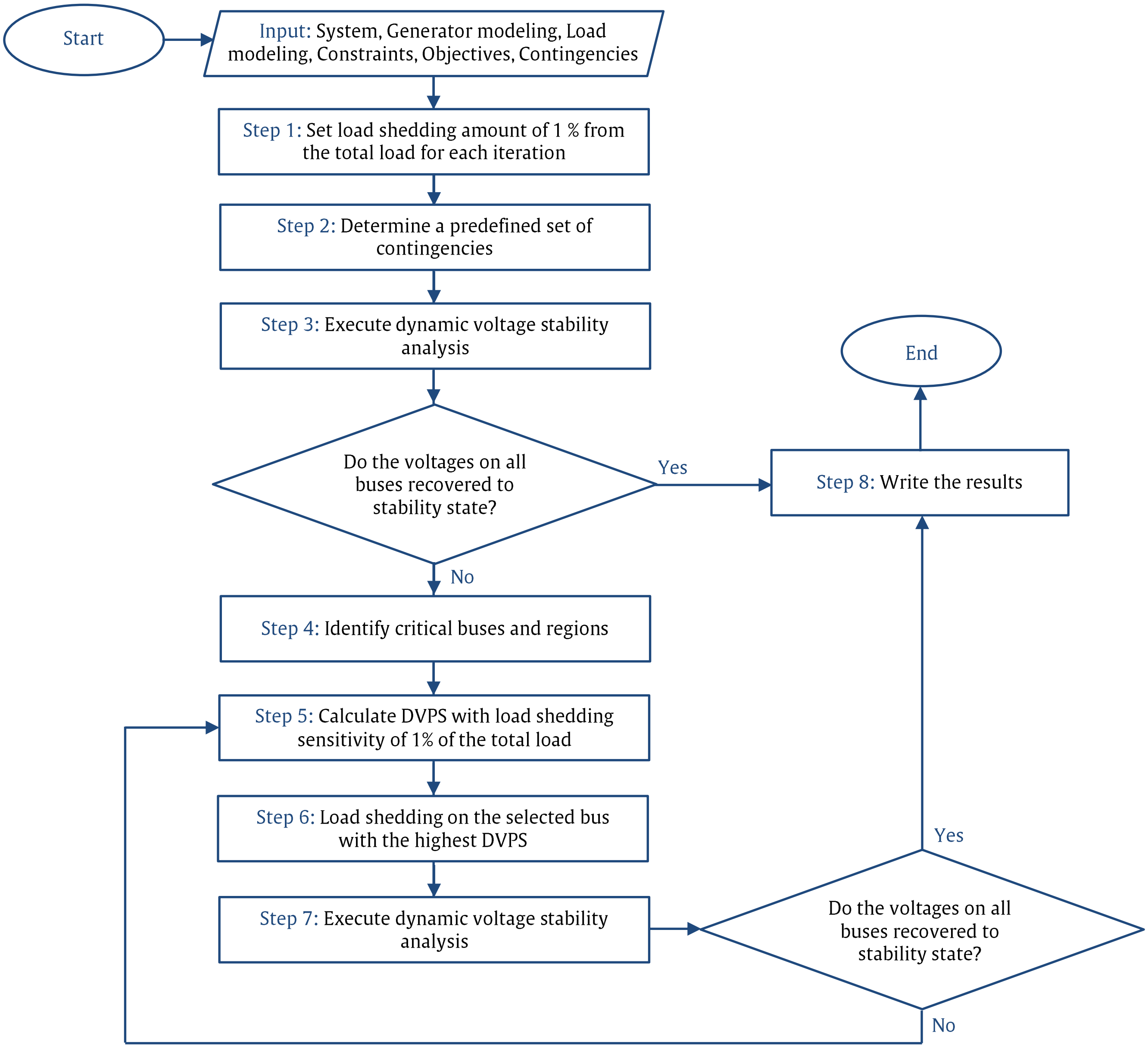

Fig. 3 Flowchart of the proposed UVLS scheme

The voltage stability margin (VSM) is computed by using the PV curve methods [5]. VSM is stated as the growth of the total load in the region of load addition which is calculated from the base case state to the maximum power transfer (PV curve nose point) signified in MW or percentage. The VSM can be computed with this relation

$$VSM\ (\%) = \frac{\lambda_k^{max} - \lambda_{base}}{\lambda_k^{max}} \text{ x } 100\% \tag{24}$$

where $\lambda_{base}$ is the basic loading parameter for basic case operations and $\lambda_k^{max}$ is the maximum loading parameter for particular circumstances.

## 4. The Test System: South Sulawesi Power System

### *4.1 Overview of the Study System [30]*

The South Sulawesi interconnection power system comprises of various power plants interconnected by several high voltage transmission lines with the provincial capital of Makassar City. The South Sulawesi system has a typical feature where the main cost-effective power plants are positioned in the north of the system, whereas the major load center is found in the south. The total power generations in the northern part of the system is 384.9 MW whereas total generation in the southern part is 232.7 MW. Total peak load of the system for case study was 556.5 MW.

The load in South Sulawesi system is dominated by residential load. As center of provincial government and business, the load in Makassar City (which is the capital of the South Sulawesi province, business center for eastern Indonesia represented by buses 10, 11, 12, and 13) is dominated with dynamic loads which are commonly air conditioner and water pump loads. In addition, there are two large cement industries which are connected to bus 8. Fig. 4 presents the single line diagram of the case study system.

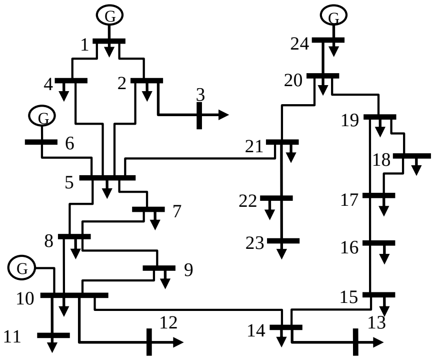

Fig. 4 The single line diagram of the case study [30]

### *4.2 Load Composition*

In this study, the load is presumed to be peak load. In the provincial capital, Makassar, (buses 10, 11, 12, and 13), the load is represented as 50% static load and 50% dynamic load, because Makassar is the province business center and its residents are generally in the middle and upper economic levels. Fig. 5 shows assumption of the load illustration in Makassar. On other buses, the load is considered as 80% static load and 20% dynamic load. In exception, on bus 8, where there are two large cement industries connected, the load is depicted as 30% static load and 70% dynamic load. Detail of the system load composition and parameters of induction motors [31] are presented respectively in Table I and Table II.

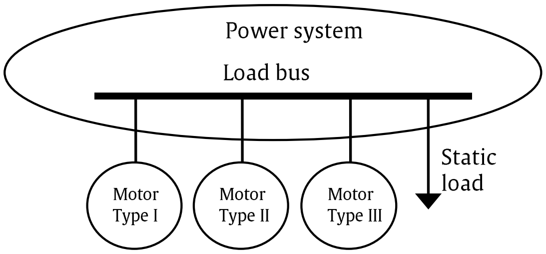

Fig. 5 Assumption of schematic representation of load at Makassar City region

TABLE I LOAD COMPOSITION

| Bus No | Load type (%) | | | | |
|---|---|---|---|---|---|
| | Static | Dynamic motor | | | |
| | | I | II | III | IV |
| 1 | 80 | 20 | - | - | - |
| 2 | 80 | 20 | - | - | - |
| 3 | 80 | 20 | - | - | - |
| 4 | 80 | 20 | - | - | - |
| 5 | 80 | 20 | - | - | - |
| 6 | 80 | 20 | - | - | - |
| 7 | 80 | 20 | - | - | - |
| 8 | 30 | 20 | - | - | 50 |
| 9 | 80 | 20 | - | - | - |
| 10 | 50 | 20 | 25 | 5 | - |
| 11 | 50 | 20 | 25 | 5 | - |
| 12 | 50 | 20 | 25 | 5 | - |
| 13 | 50 | 20 | 25 | 5 | - |
| 14 | 80 | 20 | - | - | - |
| 15 | 80 | 20 | - | - | - |
| 16 | 80 | 20 | - | - | - |
| 17 | 80 | 20 | - | - | - |
| 18 | 80 | 20 | - | - | - |
| 19 | 80 | 20 | - | - | - |
| 20 | 80 | 20 | - | - | - |
| 21 | 80 | 20 | - | - | - |
| 22 | 80 | 20 | - | - | - |
| 23 | 80 | 20 | - | - | - |
| 24 | 80 | 20 | - | - | - |

TABLE II INDUCTION MOTOR PARAMETERS [31]

| Motor type | I | II | III | IV |
|---|---|---|---|---|
| Stator resistance - $R_s$ | 0.077 | 0.064 | 0.013 | 0.013 |
| Stator leakage reactance – $X_s$ | 0.107 | 0.091 | 0.14 | 0.067 |
| Magnetizing reactance - $X_m$ | 2.22 | 2.23 | 2.4 | 3.8 |
| Rotor resistance - $R_r$ | 0.079 | 0.059 | 0.009 | 0.009 |
| Rotor leakage resistance - $X_r$ | 0.098 | 0.071 | 0.12 | 0.17 |
| Rotor inertia constant - $H$ | 0.74 | 0.34 | 0.8 | 1.5 |
| Load factor | 0.46 | 0.8 | 0.7 | 0.8 |

| | | |
|---|---|---|
| Where | Type I | Weighted cumulative of residential motors |
| | Type II | Weighted cumulative of air conditioning dominant motors |
| | Type III | Water pump |
| | Type IV | Large industrial induction motors |

## 5. Case Studies and Analysis

Since the total load is 556.5 MW, therefore the load shedding amount for each DVPS computation is set at 1% or about 5 MW. Two cases were observed in this case study: the first case was an outage between buses 8 and 10, and the second was an outage between buses 17 and 19.

### *5.1 Case 1: Outage between bus 8 and 10*

Fig. 7 shows the voltage collapse after a disturbance has occurred which causes the loss of the transmission line between buses 8 and 10. Because of this outage, there are 3 unstable regions detected: Makassar City region (buses 10 - 14), buses 8 and 9; and buses 22 and 23 where the voltage collapse in these regions are shown in Figs. 8, 9, and 10 correspondingly. Specifically from Fig. 8, this clearly illustrates a substantial voltages drop in the Makassar substations which drop to voltage of 0.66 – 0.69 pu at time *t*=30 s. This is due to the fact that Makassar as the load center in the South Sulawesi system has significant large quantity of dynamic induction motor loads. Because induction motors have troubles accelerating after big perturbance then they stall and distress the voltage in the Makassar region.

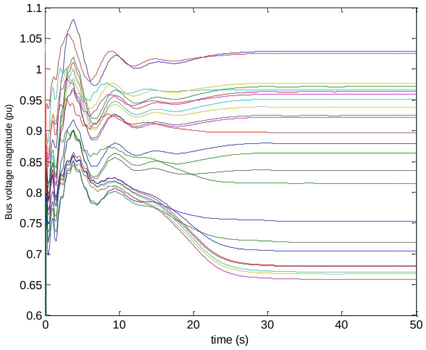

Fig. 7 Voltage declines in all buses after interruptions between buses 8 and 10

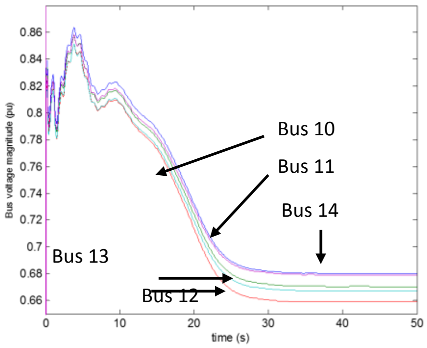

Fig. 8 Voltage declines in buses 10 – 14 after interruptions between buses 8 and 10

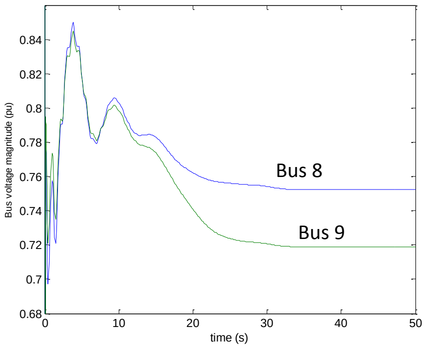

Fig. 9 Voltage declines in buses 8 and 9 after interruptions between buses 8 and 10

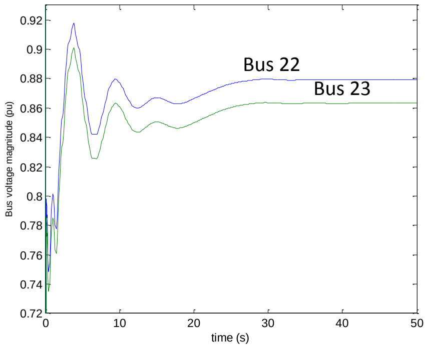

Fig. 10 Voltage declines in buses 22 and 23 after interruptions between buses 8 and 10

In this simulation, the voltage stability constraint is violated, therefore load shedding is required to retrieve stability. Dynamic sensitivity analysis is carried out to evaluate the impact of 5 MW load shedding on each bus in the critical unstable region. Fig. 11 and Fig. 12 illustrate the sensitivities of dynamic voltage curve of unstable buses for the first iteration if 5 MW load shedding is applied to bus 13 and bus 3, respectively. It can been concluded from both figures, that the sensitivity of dynamic voltage curve for 5 MW load shedding on bus 13 are better than the dynamic voltage curve sensitivity for 5 MW load shedding on bus 3. Furthermore, DVPS as defined in Eq. (21) is computed to present a distinctive indicator for location of load shedding. In calculating the DVPS values, we used a time interval 0.5 seconds for a period 0 – 10 second and 1 second for a duration of 10 – 30 seconds. The reason for this is because the voltages very fluctuate during the first 10 seconds after disturbance. Table III presents the DVPS computation for 5 MW load shedding on buses 13 and 3.

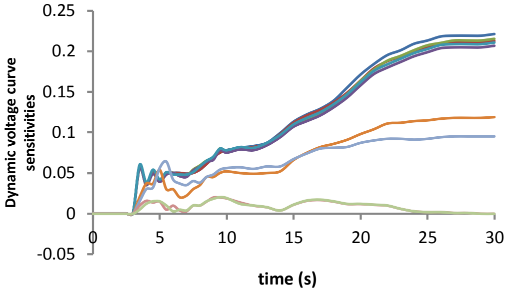

Fig. 11 Dynamic voltage curve sensitivities if a 5 MW load shedding is applied to bus 13

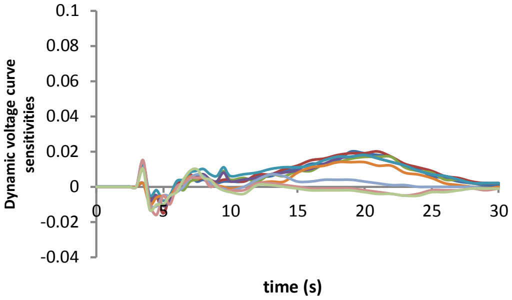

Fig. 12 Dynamic voltage curve sensitivities if a 5 MW load shedding is applied to bus 3

TABLE III DVPS CALCULATION

| | $\sum_{t=0}^{t_s}\left[\frac{\partial V_i}{\partial P_j}\right]_{t=t_k}$ | |
|---|---|---|
| Bus $j$ | 13 | 3 |
| Bus $i$ | | |
| 12 | 4.051 | 0.187 |
| 13 | 3.957 | 0.22 |
| 11 | 3.934 | 0.184 |
| 14 | 3.829 | 0.188 |
| 10 | 3.933 | 0.257 |
| 9 | 2.352 | 0.125 |
| 8 | 2.222 | 0.038 |
| 23 | 0.326 | -0.041 |
| 22 | 0.314 | -0.047 |
| DVPS Value | 24.918 | 1.111 |

Fig. 13 informs the DVPS value in the first iteration for 5 MW sensitivity in each load bus. As the result, bus 13 has the highest DVPS value (24.92) and it is indicated with red bar. Load curtailment of 5 MW is evaluated on bus 13 and the system voltage performance is re-assessed. In this phase, the system voltage is not able to improve back to its stability condition, hence the dynamic voltage curve sensitivities are executed again to compute DVPS. For this outage, this process was done in 6 iterations until the constraints are met and the results of DVPS value in each iteration are given in Table IV. Therefore, we obtained the load shedding locations for this case are buses 13 (15 MW), 9 (5 MW) and 23 (10 MW) and are summarized in Table V. Fig. 14 shows the results of the voltage enhancement after load curtailment with a total of 30 MW on buses 13, 9 and 23. This obviously verifies that all voltages have significantly improved and the system stability has been retrieved.

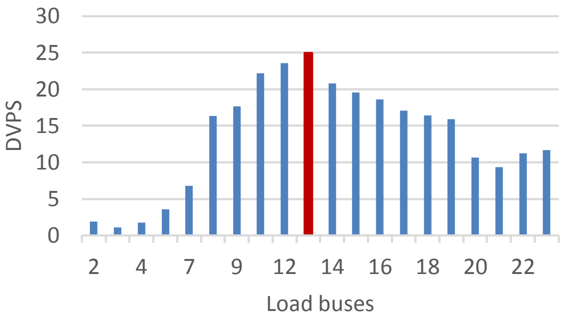

Fig. 13 DVPS value in the first iteration

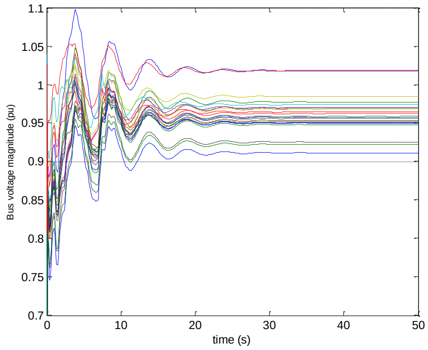

Fig. 14 Voltage improvement after 30 MW load shedding on buses 13, 9 and 23 for Case 1

TABLE IV DVPS VALUE

| | DVPS | | | | | |
|---|---|---|---|---|---|---|
| Iteration | I | II | III | IV | V | VI |
| Bus No | | | | | | |
| 2 | 1.91 | 1.24 | 1.03 | 0.87 | 0.77 | 0.53 |
| 3 | 1.11 | 0.97 | 0.78 | 0.57 | 0.46 | 0.32 |
| 4 | 1.76 | 1.12 | 0.98 | 0.76 | 0.65 | 0.44 |
| 5 | 3.56 | 2.79 | 2.11 | 1.95 | 1.76 | 1.32 |
| 7 | 6.79 | 5.35 | 4.05 | 3.34 | 2.56 | 1.06 |
| 8 | 16.34 | 14.11 | 13.33 | 9.12 | 6.34 | 5.12 |
| 9 | 17.66 | 15.23 | 14.12 | 9.88 | 5.65 | 5.45 |
| 11 | 22.17 | 18.98 | 12.56 | 9.69 | 1.78 | 1.56 |
| 12 | 23.57 | 20.04 | 13.02 | 10.03 | 1.89 | 1.32 |
| 13 | 24.92 | 21.32 | 13.78 | 10.65 | 1.12 | 0.95 |
| 14 | 20.76 | 17.64 | 11.45 | 9.34 | 1.67 | 0.65 |
| 15 | 19.57 | 15.87 | 10.87 | 8.67 | 3.76 | 2.89 |
| 16 | 18.63 | 13.96 | 9.98 | 7.67 | 4.78 | 3.23 |
| 17 | 17.05 | 12.31 | 9.02 | 6.99 | 4.03 | 3.54 |
| 18 | 16.4 | 11.44 | 8.34 | 6.12 | 5.78 | 3.97 |
| 19 | 15.89 | 9.98 | 7.86 | 5.46 | 4.78 | 3.89 |
| 20 | 10.67 | 7.02 | 5.79 | 4.67 | 3.78 | 3.08 |
| 21 | 9.34 | 5.95 | 4.57 | 3.56 | 2.88 | 2.01 |
| 22 | 11.23 | 10.28 | 8.79 | 8.12 | 7.65 | 6.45 |
| 23 | 11.68 | 10.57 | 9.86 | 9.55 | 8.78 | 8.12 |

TABLE V LOAD SHEDDING LOCATIONS FOR CASE 1

| Location | Amount (MW) |
|---|---|
| 13 | 15 |
| 9 | 5 |
| 23 | 10 |

As a comparison, this work also observes at how the voltage improvement if the load shedding is carried out on bus 13 only for 30 MW, because in the first iteration bus 13 has the highest DVPS value. Very interesting, even though the voltage magnitude increase but voltage on buses 8 and 23 cannot improve back to the stability constraints. Fig. 15 shows the voltage behavior after 30 MW load shedding on bus 13. Therefore, it is not suggested to perform load shedding on bus 13 for 30 MW, although in the first iteration, bus 13 has the highest DVPS. By assessing the load shedding location with a smaller amount, this can provide more efficient load shedding scheme.

This work also investigates and compares load shedding based on the utility schemes. The state electricity utility had load shedding design with total load shedding of 31.64 MW and are located on buses 19, 22, 4, 2, 3, 24 and 18 as shown in Table VI. Fig. 16 shows the voltage behavior after load shedding on these buses and confirms that with this arrangement, the system voltage stability cannot recover back to the stability constraints. It can be seen that after load curtailment, the system voltage can slightly increase, but after *t*=40 s, the voltage in the Makassar region drop significantly to approximately 0.66 p.u. This condition is the same as if there was no load shedding. Therefore, this load shedding scheme is not as effective and efficient as our proposed scheme. Consequently, more load shedding amount is required in order to comply with the system voltage stability constraints and it is not recommended to perform load shedding on these buses. Table VII presents a comparison between the results of our proposed methodology and the utility scheme.

TABLE VI UTILITY LOAD SHEDDING SCHEME [30]

| No | Substation | MW |
|---|---|---|
| 1 | 19 | 4.44 |
| 2 | 22 | 4.5 |
| 3 | 4 | 4.38 |
| 4 | 2 | 3.27 |
| 5 | 3 | 1.53 |
| 6 | 24 | 10.38 |
| 7 | 18 | 3.15 |
| Total load shedding | | 31.64 |

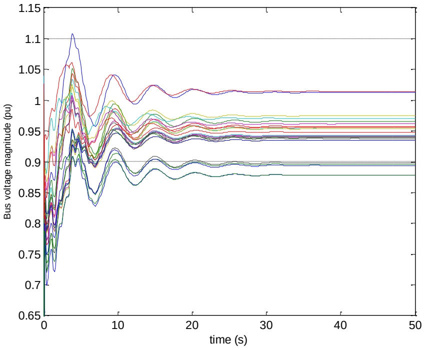

Fig. 15 Voltage performance after 30 MW load curtailment on bus 13

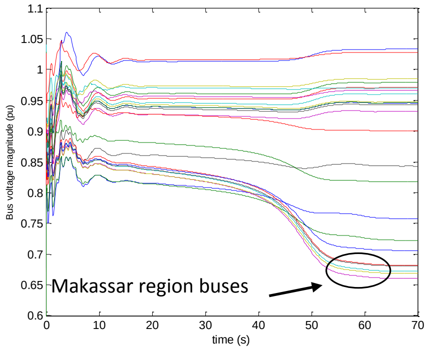

Fig. 16 Voltage performance after the state utility load shedding scheme

TABLE VII SUMMARY FOR CASE 1

| Scheme | Load shedding | | Remarks |
|---|---|---|---|
| | Location | Total (MW) | |
| Proposed method | 13, 9, 23 | 30 | Stable |
| Utility scheme (Table VI) | 19, 22, 4, 2, 3, 24, 18 | 31.64 | Not stable |

The VSM is assessed on the most critical bus after outage which is bus 12. From Fig. 6, this bus has the lowest voltage magnitude. The base load on bus 12 is 119.2 MW. Fig. 17 shows bus 12 PV curve for pre-contingency condition with $\lambda^{max}$ of 1.37 which gives 27% VSM. The complete VSM calculation for all other conditions can be seen in Table VIII. From

Table VIII, the VSM for post-contingency condition is only -4.17%. The negative value of VSM indicates the system instability, therefore precautions are required to preclude the system from voltage collapse. In addition, Table VIII also presents the VSM values for after load shedding conditions. As shown in Fig. 14, the system voltage can improve back to stable situation after load shedding on the buses based on proposed method. This is clarified with a positive VSM value of 11.86%. Whereas Fig. 16 shows the system still unstable after load shedding based on the existing scheme from the utility and the VSM is also negative (-2.04%). From this, we can see the results of the VSM calculations are consistent with the dynamic simulation results so as to prove the robustness of the proposed DVPS based UVLS scheme.

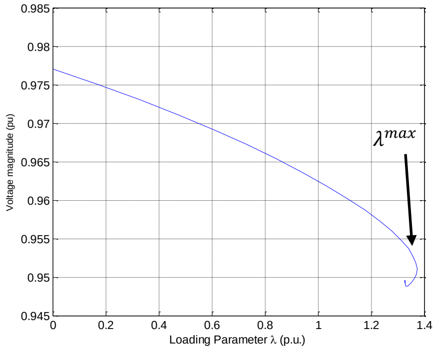

Fig. 17 Pre-contingency PV curve of bus 12

TABLE VIII VOLTAGE STABILITY MARGIN

| Condition | $\lambda^{max}$ | VSM (%) |
|---|---|---|
| Pre-contingency | 1.37 | 27 |
| Post-contingency | 0.96 | -4.17 |
| Load shedding (proposed method) | 1.11 | 11.86 |
| Load shedding based on utility scheme | 0.98 | -2.04 |

### *5.2 Case 2: Outage between buses 17 and 19*

For Case 2, the total system load is the same as Case 1, but the fault location is different.

The outage is between buses 17 and 19. The voltage declines after the disturbance is given in Fig. 18.

The voltage behavior is similar to that in Case 1. In this case, there are 3 critical regions as well: Makassar City, bus 8 and bus 23. The same process as in Case 1 is also applied in Case 2. For this case, the process of calculating the location and the amount of load shedding was done in 6 iterations so that the total load shedding is 30 MW, the same as the amount of load shedding in Case 1. However, the location of the load shedding is slightly different. For this outage, the load shedding should be done on bus 12 for 10 MW, bus 8 for 5 MW, bus 13 for 5 MW and bus 23 for 10 MW as shown in Table IX. The voltage improvement after load shedding on these buses is illustrated in Fig. 19. Table X provides the differences in load shedding scheme for the two cases. It can be concluded that the amount and location of load curtailment also depend on the fault location.

TABLE IX LOAD SHEDDING LOCATIONS FOR CASE 2

| Location | Amount (MW) |
|---|---|
| 12 | 10 |
| 8 | 5 |
| 13 | 5 |
| 23 | 5 |

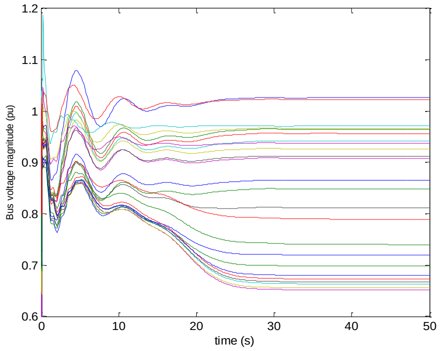

Fig. 18 Voltage declines in all buses after interruptions between buses 17 and 19

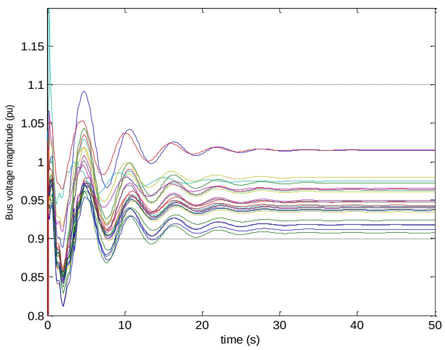

Fig. 19 Voltage improvement after 30 MW load shedding on buses 12, 8, 13 and 23 for Case 2

TABLE X COMPARISON BETWEEN CASE 1 AND CASE 2

| Case (Outage) | Load shedding | | |
|---|---|---|---|
| | Location | Amount (MW) | Total (MW) |
| I (Buses 8 - 10) | 13 | 15 | 30 |
| | 9 | 5 | |
| | 23 | 10 | |
| II (Buses 17 – 19) | 12 | 10 | 30 |
| | 8 | 5 | |
| | 13 | 5 | |
| | 23 | 10 | |

## 6. Conclusions

This paper recommends a novel under voltage load shedding design to stabilize the system after large perturbance and to ensure the system secure constrains are fulfilled. The UVLS scheme is designed based on dynamic sensitivities method that calculate dynamics sensitivity related to system constraints and provide a technique of calculating variations in the system variables with respect to rapid changes in system initial conditions and parameters . In this work, dynamic sensitivity is utilized to verify the minimum amount of load curtailment and to decide location of load curtailment.

This method is used to evaluate the South Sulawesi system in Indonesia. Two cases were studied, the first outage was between buses 8 and 10 and the second case was an outage between buses 17 and 19. The calculation of the dynamic sensitivity index has indicated different buses as load shedding location. The dynamic simulation results as well as the calculations of the voltage stability margin confirm the robustness of the proposed method compared to the load shedding scheme used by the utility. The dynamic sensitivity index gives convenient information for finding the most appropriate location for load shedding. Finally, it is worth to be clarified that the proposed UVLS methodology consists of broad method and procedure that can be implemented in designing a more realistic, reliable and effective approach to dynamic UVLS that takes into account the modeling of loads to any power system.

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# CREDIT AUTHOR STATEMENT

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**Muhammad Bachtiar Nappu**: Software, Simulation, Investigation and Validation.

**Zhao Yang Dong**: Conceptualization, Methodology, Supervision, Reviewing and Editing.

Electric Power Systems Research

# Dynamic Under-Voltage Load Shedding Scheme Considering Composite Load Modeling

--Manuscript Draft--

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| **Abstract:** | This manuscript recommends an under-voltage load shedding scheme based on the sensitivity of dynamic voltage curves to mitigate voltage collapse in highly stressed power systems. The developed method can be used to determine the minimum amount and proper locations of load curtailment by considering power system dynamics including dynamic load modeling. The selected Indonesian regional system has a large number of dynamic loads in form of air conditioning and water pump loads whose dynamics contribute considerably to the complexity of the power system stability. Loss of the transmission line in the system caused by the impact of the composite load after major disturbance is studied. The proposed scheme involves an iterative procedure based on the sensitivity analysis of the dynamic voltage curve to solve the problem of load shedding. Furthermore, this work developed a new index named dynamic voltage-active power sensitivity (DVPS). The DVPS is calculated in all load buses to give information about the bus that has a predominant influence on improving system voltage stability through load shedding. The results of this work show a noteworthy improvement in the magnitude of the voltage level as well as the voltage stability margin. |

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3 May 2021

Dear Professor Carlo Alberto Nucci, Editor-in-Chief of Electric Power Systems Research,

We wish to submit the revised version of our research article entitled "**Dynamic Under Voltage Load Shedding Scheme Considering Composite Load Modeling**" for consideration by Electric Power Systems Research. We confirm that this work is original and has not been published elsewhere, nor is currently under consideration for publication elsewhere. We have made changes and revisions according to the reviewers' comments.

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Please address all correspondence concerning this manuscript to me at ardiaty@eng.unhas.ac.id.

Thank you for your consideration of this manuscript.

Sincerely yours,

Ardiaty Arief, Ph.D.

## HIGHLIGHTS

- A novel under-voltage load shedding (UVLS) scheme is developed using dynamic voltage stability analysis.
- Detailed static and dynamic load modeling are considered, and load compositions are included for a more realistic, reliable, and effective UVLS design.
- A new formulation of dynamic voltage active power sensitivity (DVPS) is formulated to determine location and amount of load shedding.

# Dynamic Under-Voltage Load Shedding Scheme Considering Composite Load Modeling

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*Abstract*—This manuscript recommends an under-voltage load shedding scheme based on the sensitivity of dynamic voltage curves to mitigate voltage collapse in highly stressed power systems. The developed method can be used to determine the minimum amount and proper locations of load curtailment by considering power system dynamics including dynamic load modeling. The selected Indonesian regional system has a large number of dynamic loads in form of air conditioning and water pump loads whose dynamics contribute considerably to the complexity of the power system stability. Loss of the transmission line in the system caused by the impact of the composite load after major disturbance is studied. The proposed scheme involves an iterative procedure based on the sensitivity analysis of the dynamic voltage curve to solve the problem of load shedding. Furthermore, this work developed a new index named dynamic voltage-active power sensitivity (DVPS). The DVPS is calculated in all load buses to give information about the bus that has a predominant influence on improving system voltage stability through load shedding. Dynamic simulations are carried out with an Indonesian power system, the South Sulawesi interconnection power system with the proposed load shedding scheme. The results of this work show a noteworthy improvement in the magnitude of the voltage level as well as the voltage stability margin.

*Keywords*—dynamic load modeling, dynamic voltage curve sensitivity, under-voltage load shedding, voltage stability, voltage stability margin.

## Nomenclature

| | |
|---|---|
| DVPS | dynamic voltage-active power sensitivity |
| UVLS | under-voltage load shedding |
| VSM | voltage stability margin |
| $E_d^{\prime}$ | *d*-axis stator transient voltage related to rotor transient flux component |
| $E_q^{\prime}$ | *q*-axis stator transient voltage related to rotor transient flux component |
| $E_f^{*}$ | field voltage |
| $H$ | inertia constant |
| $I_d$ | *d*-axis element of stator current |
| $I_q$ | *q*-axis element of stator current |
| $T_{do}^{\prime}$ | *d*-axis transient time constant |
| $T_{qo}^{\prime}$ | *q*-axis transient time constant |
| $T_{do}^{\prime\prime}$ | *d*-axis subtransient time constant |
| $T_{qo}^{\prime\prime}$ | *q*-axis subtransient time constant |
| $T_{FW}^{*}$ | extra damping torque in comparison to rotor speed |
| $T_M$ | mechanical torque |
| $X_d^{\prime}$ | *d*-axis transient reactance |
| $X_q^{\prime}$ | *q*-axis transient reactance |
| $X_d^{\prime\prime}$ | *d*-axis subtransient reactance |
| $X_q^{\prime\prime}$ | *q*-axis subtransient reactance |
| $X_{ls}$ | armature leakage reactance |
| $\delta$ | generator rotor power angle |
| $\psi_d$ | subtransient EMFs as a result of *d*-axis damper flux linkage |
| $\psi_q$ | subtransient EMFs as a result of *q*-axis damper flux linkage |
| $\omega$ | generator rotor angular speed |
| $\omega_s$ | generator synchronous rotor speed ($2\pi f$) |
| $P_{Li}$ | active load on the bus *i* |
| $Q_{Li}$ | reactive load on the bus *i* |
| $P_{Li}^{0}$ | active load according to the initial bus voltage |
| $Q_{Li}^{0}$ | reactive load according to the initial bus voltage |
| $\alpha_P$ | constant impedance element of the active load |
| $\alpha_Q$ | constant impedance element of the reactive load |
| $\beta_P$ | constant current element of the active load |
| $\beta_Q$ | constant current element of the reactive load |
| $\gamma_P$ | constant power element of the active load |
| $\gamma_Q$ | constant power element of the reactive load |
| $V_i$ | actual operating voltage at bus *i* |
| $P_s(V)$ | steady state active power load as function of voltage |
| $Q_s(V)$ | steady state reactive power load as function of voltage |
| $P_t(V)$ | transient active power load as function of voltage |
| $Q_t(V)$ | transient reactive power load as function of voltage |
| $P_d$ | instantaneous active power |
| $Q_d$ | instantaneous reactive power |

| | |
|---|---|
| $T_p$ | active power time constant |
| $T_q$ | reactive power time constant |
| $x_p$ | active power load state variable |
| $x_q$ | reactive power load state variable |
| $P_{shed_j}$ | load shedding quantity on bus $j$ |
| $n_k$ | critical buses number |
| $t_k$ | instantaneous time |
| $t_s$ | number of instantaneous time |

# 1. Introduction

## *1.1 Background and Motivations*

Since the last century, the stability of the electric power system has been believed as an important precondition for a secure and stable operation of the power system [1]. As the power system expands to a more complex and highly stressed system, with the increasing number of interconnections, renewable energy resources integration, direct current transmission system as well as electricity market, the problem of voltage stability also becomes more crucial, since the stability characteristics of the system become more complicated than before [2]. During the power system scheduling and operation, the problem of voltage stability has been of major interest, due to the considerable amount of system failures caused by voltage instability which is usually caused by a power outage or a sudden increase in load. There are two common defense measures to prevent voltage instability, namely preventive measures, and corrective measures. Preventive measures are taken in a pre-contingency state to improve the margin of voltage security, while corrective measures are usually carried out during post-interference configurations to reinstate system stability. Among the various precautions that can be implemented to preclude voltage instability, under-voltage load shedding (UVLS) becomes more acceptable as an inexpensive and reliable corrective measure. Nevertheless, the UVLS must be the final remedial defense when no other alternative is available to prevent the possibility of a voltage collapse. UVLS plays an important role in power system control and stability when the system is experiencing major disruptions.

The load shedding design must be "robust". The UVLS design must cover sufficient load to be shed but simultaneously not be over-sensitive. The philosophy of UVLS is that if there is a disturbance in the system and the voltage drops to a certain predetermined level within a certain period then a predetermined amount of load is shed from the system [3]. The purpose is that the system voltage returns to its stability limit when a certain amount of load is disconnected from the system.

Research and experience have proven that UVLS is an excellent countermeasure against voltage instability. In this part, we will provide a brief overview of UVLS using the IEEE 14 bus Reliability Test System as shown in Fig. 1 as an example. It is assumed that there is an outage between bus 6 and bus 13. Figs. 2 (a) and (b) show the voltage drop after the fault across all buses and the critical buses, respectively. Then Fig. 2 (c) demonstrates the voltage recovery after load shedding.

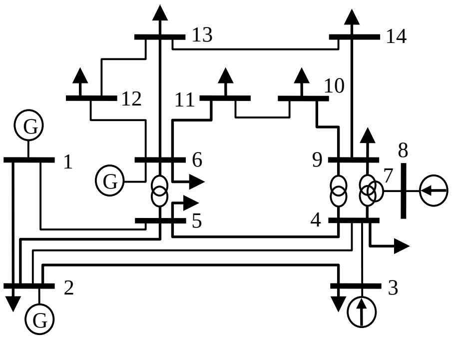
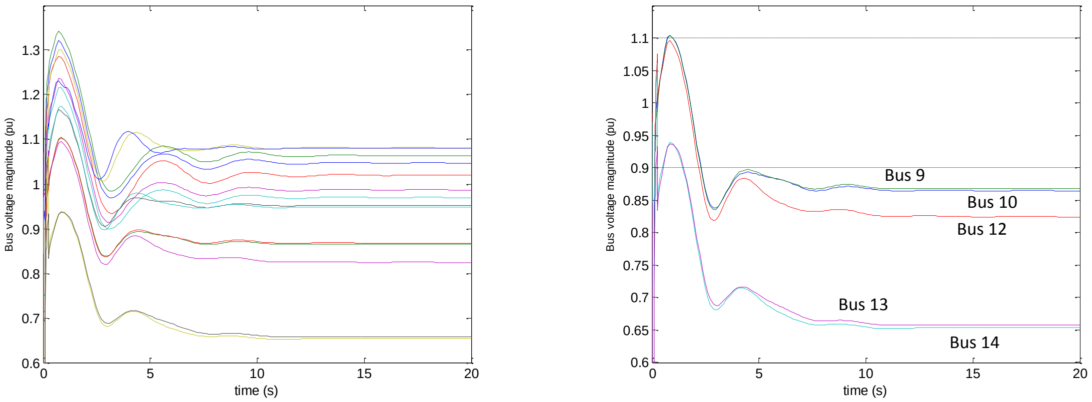
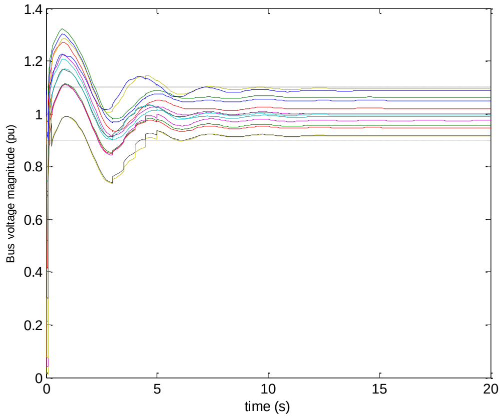


Fig. 1 The IEEE 14 Bus Reliability Test System



(a) Voltage drop across all buses

(b) Voltage drop across the critical buses



(c) Voltage recovery after load shedding

Fig. 2 Voltage performance after disturbance and load shedding

### *1.2 State-of-the-art of Power System Under-Voltage Load Shedding*

Various research had been conducted to investigate preventive and corrective actions to preclude instability using voltage stability analysis, which is an imperative instrument for predicting probable instability and generally can be categorized into static, quasi-static, and dynamic voltage stability analysis. In the literature, numerous methods have been utilized to design effective UVLS schemes. Most of them use static or dynamic voltage stability analysis. This section will provide an overview of existing UVLS methods. The authors in [4] developed an optimization model with relaxation restrictions to compute minimal load shedding. A load shedding based on modal participation factors was proposed in [5] to identify load shedding location. The multistage method for deciding the location and minimum amount of load curtailment was presented in [6]. The author in [7] developed UVLS based on integer value modeling and presented the interruption penalty factor for feeders and the participation penalty factor for buses to minimize the total curtailment of the load. A load shedding was designed by using Particle swarm optimization (PSO) in [8]. Teaching learning-based optimization (TLBO) was implemented in [9] for load shedding and the locations for load shedding were determined by using the severity index sensitivity. The work in [10] formulated an improved risk-based AC security-constrained optimal power flow (RB-SCOPF) for load shedding amount. Another OPF based UVLS to determine the amount, place, degree, and timing of load shedding to maintain a predetermined voltage stability margin was proposed by [11] and Linear optimization-based optimal power flow (LP-OPF) for load shedding was suggested by [12]. The work in [13] established load shedding requirements of the extended equal area criterion (EEAC). The authors in [14] recommended a technique for determining load shedding location by taking into consideration multi-contingencies by tracking the stability index and for computing load shedding amount by using a modified fuzzy logic system. Hybrid Imperialist Competitive Algorithm-Pattern Search (HICA-PS) was employed for load shedding in [15]. In paper [16], the authors presented a load shedding scheme by using the eigenvalue of the Jacobian matrix to determine load shedding location and using Genetic Algorithm (GA) and Neural Network (NN) to compute load shedding amount. However, these UVLS schemes were developed based on the static voltage analysis approach. The drawback of the static voltage analysis technique is that it cannot justify the dynamic character of the occurrences of voltage collapse. The static and quasi-static voltage stability analyses are based on the power flow snapshots and these methods do not take into consideration the dynamic modeling of the system. On the other hand, time-domain simulations hold an important role in assessing the voltage collapse phenomena mechanism.

The studies in [17-21] investigated UVLS schemes based on time-domain simulations. A UVSL based on adaptive model predictive control (MPC) was developed by [17]. A remedial action scheme (RAS) was created in [18] where candidates for load shedding location were ranked according to their categories and influences on the system stability and enactment. The authors in [19] analyzed the impacts of grid behavior with various UVLS schemes. The study in [20] presented a wide area voltage stability index-based load shedding scheme and used a modified Discrete Imperialistic Competition Algorithm (DICA) to solve the load shedding. Even though these studies proposed UVLS based on time-domain simulations, yet in these works, detailed load modeling (static and dynamic load models) are not considered. Nevertheless, load modeling is important and holds a vital part in the assessment of dynamic voltage stability as well as the design of UVLS, hence proper modeling of the load will give a significant impact on the accuracy of the simulation results.

### *1.3 Contributions of This Paper*

Based on the discussion above, there were a considerable number of research works that have investigated and proposed different UVLS schemes. However, these studies have no consideration for detailed load modeling and do not fully take into account the system dynamic modeling particularly from the majority proportion of induction motor loads in a power system.

In the modern power system with a substantial quantity of air conditioning loads, with only a static load model in time-domain simulation is inadequate to evaluate the process of voltage collapse. Especially in Indonesia, several systems are featured with significant air conditioning and pumping loads. As the power system becomes profoundly stressed and works at its boundaries with reduced capacity and stability margins, a more precise representation of load characteristics becomes more vital. Instability in a power system with a considerably large quantity of dynamic motor loads can result in slow voltage improvement or rapid voltage drop [22]. The deficiency of dynamic load modeling in the time domain simulation is assumed to be the main reason for the inconsistencies between real measurements and simulation outcomes [23]. Motors have trouble accelerating after main interruptions and can distress voltage profile improvement [24]. Induction motors may stall and draw high currents and result in an increase in voltage drop in some areas in the system. To plan a robust UVLS scheme, it is essential to precisely represent the load model inclusive of induction motors. Therefore, for financial reasons, it is crucial to determine a technique for optimum and more precise load shedding that incorporates dynamic induction motor models.

In this paper, a new analytic and systematic method is suggested to design a strategic under-voltage load shedding scheme that incorporates dynamic voltage sensitivity analysis as an approach for computing the amount and location of load curtailment in a power system. The developed method comprises an iterative procedure that calculates the bus dynamic voltage sensitivities concerning the amount of load shedding. At each stage, the load shedding quantity is set to a small amount of about 1% of the total load. Additionally, a new formulation, namely dynamic voltage-active power sensitivity (DVPS) is created based on dynamic voltage sensitivities to decide the location of load shedding. Furthermore, the proposed UVLS scheme is evaluated based on the voltage stability margin. The amount of load shedding 1% for each iteration is considered sufficient to calculate the total amount of load shedding. However, it is possible to reduce the amount of load shedding per iteration. A more optimal amount of total load shedding can be obtained but more iterations are required. On the other hand, increasing the amount of load shedding per iteration will result in the possibility of a more calculated amount of load shedding than is needed (over shedding).

Therefore, to fulfill this imperative research gap, this work aims to deliver these novel contributions:

i. A new UVLS scheme is developed using dynamic voltage stability analysis;
ii. Detailed static and dynamic load modeling are considered, and load compositions are included for a more realistic, reliable, and effective UVLS design; and
iii. A new formulation of dynamic voltage active power sensitivity (DVPS) is formulated to determine the location and amount of load shedding.

The UVLS method developed in this paper involves multistage or iterative solutions. The main reason for this iterative process is to minimize the load shedding amount by analyzing its dynamic sensitivity with a small amount of load shedding for every iteration until the system is stable hence the optimal or minimum amount for load shedding can be obtained.

The remainder of this paper is organized as follows: Section 2 provides an explanation about power system modeling for the UVLS design. Section 3 outlines the proposed methodology: the dynamic voltage sensitivities enhanced UVLS scheme. Section 4 specifically gives information about the South Sulawesi system in Indonesia. Section 5 provides the results and analysis then Section 6 concludes the research key outcomes. These work results are expected to deliver a better set of UVLS to deal with the possibility of voltage collapse occurrence, particularly in the South

Sulawesi power system.

## 2. Power Systems Modeling for Under-Voltage Load Shedding Studies

The first step of dynamic voltage stability assessment is to have a reliable power system model. This includes key elements of a power system, i.e. generators, network, and loads for both steady-state and dynamic. The following section describes the system modeling for the proposed UVLS scheme.

### *2.1 Synchronous Generator Modeling*

The synchronous generator model employed in this work is the detailed 6th order synchronous machine model. The 6th order synchronous machine model considers four windings with the existence of a field circuit and supplementary circuit by the *d*-axis and two further circuits through the *q*-axis. Nevertheless, the network and stator transients in the 6th order model are ignored. The dynamics generated by these transients are negligible and would give slightly conservative results, which are more suitable for dynamic analysis, predominantly for fast screening to identify and recognize all critical and unstable consequences [25]. In dynamic voltage stability, the differential equations overseeing the sub transient behavior of the 6th order synchronous machines are given by the following equations [26],

$$T_{do}^{'}\frac{dE_q^{'}}{dt} = -E_q^{'} - \left(X_d - X_d^{'}\right)\left[I_d - \left(\frac{X_d^{'} - X_d^{''}}{\left(X_d^{'} - X_{ls}\right)^2}\right)\left\{\psi_d + \left(X_d^{'} - X_{ls}\right)I_d + E_q^{'}\right\}\right] + E_f^{*} \tag{1}$$

$$T_{do}^{''}\frac{d\psi_d}{dt} = -\psi_d + E_q^{'} - \left(X_d^{'} - X_{ls}\right)I_d \tag{2}$$

$$T_{qo}^{'}\frac{dE_d^{'}}{dt} = -E_d^{'} + \left(X_q - X_q^{'}\right)\left[I_q - \left(\frac{X_q^{'} - X_q^{''}}{\left(X_q^{'} - X_{ls}\right)^2}\right)\left\{\psi_q + \left(X_q^{'} - X_{ls}\right)I_q + E_d^{'}\right\}\right] \tag{3}$$

$$T_{qo}^{''}\frac{d\psi_q}{dt} = -\psi_q + E_d^{'} - \left(X_q^{'} - X_{ls}\right)I_q \tag{4}$$

$$\frac{d\delta}{dt} = \omega - \omega_s \tag{5}$$

$$\begin{aligned}\frac{2H}{\omega_s}\frac{d\omega}{dt} = {} & T_M - \left(\frac{X_d^{''} - X_{ls}}{X_d^{'} - X_{ls}}\right)E_q^{'}I_q - \left(\frac{X_d^{'} - X_d^{''}}{X_d^{'} - X_{ls}}\right)\psi_d I_q - \left(\frac{X_q^{''} - X_{ls}}{X_q^{'} - X_{ls}}\right)E_d^{'}I_d \\ & + \left(\frac{X_q^{'} - X_q^{''}}{X_q^{'} - X_{ls}}\right)\psi_q I_d - \left(X_q^{''} - X_d^{''}\right)I_d I_q - T_{FW}^{*}\end{aligned} \tag{6}$$

## *2.2 Load Modeling*

Load modeling is crucial and one of the most important elements in the dynamic voltage stability analysis included in the UVLS design. In this study, the load on each bus is demonstrated as a composite load model which is a combination of static and dynamic load components. Section 5 elaborates further details of the load configuration in this work. Fig. 3 shows the equivalent circuit of the composite load model, where *Z* is constant impedances; *I* is constant currents; *P* is constant powers; $X_m$ is the magnetization reactance; $X_s$ is the stator leakage reactance; $X_r$ is the rotor leakage resistance; $R_s$ is the stator resistance; $R_r$ is the rotor resistance, and *s* is the induction motor slip.

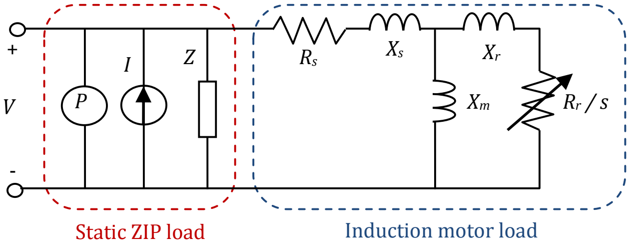


Fig. 3 Schematic circuit of the composite load model [27]

### *2.2.1 Static Load Modeling*

In general, loads depend on the voltage of a bus. Static load voltage reliance can be stated through exponential or polynomial equations. Static ZIP load modeling is commonly expressed as a voltage magnitude function on a particular bus connected to the load as [28],

$$P_{Li}(V_i) = P_{Li}^0\left[\alpha_P\left(\frac{V_i}{V_0}\right)^2 + \beta_P\left(\frac{V_i}{V_0}\right) + \gamma_P\right] \quad (7)$$

$$Q_{Li}(V_i) = Q_{Li}^0\left[\alpha_Q\left(\frac{V_i}{V_0}\right)^2 + \beta_Q\left(\frac{V_i}{V_0}\right) + \gamma_Q\right] \quad (8)$$

### *2.2.2 Dynamic Load Modeling*

Dynamic load modeling is essential for UVLS strategy since induction motors will slow down substantially when their terminal voltage declines because of short circuits. The common models for induction motor type dynamic loads are [29],

$$T_p\frac{dP_d}{dt} + V^{\alpha_t}P_d = V^{\alpha_t}P_s(V) + \alpha_t T_p\frac{P_d}{V}\frac{dV}{dt} \quad (9)$$

$$T_q\frac{dQ_d}{dt} + V^{\beta_t}Q_d = V^{\beta_t}Q_s(V) + \beta_t T_q\frac{Q_d}{V}\frac{dV}{dt} \quad (10)$$

where $\alpha_t$, $\alpha_s$, $\beta_t$, $\beta_s$, $P_1$ and $Q_1$ are constants independent of load busbar voltage $V$.

## 3. Dynamic Voltage Sensitivities Enhanced UVLS Scheme

### *3.1 Dynamic Voltage Active Power Sensitivity Analysis*

The dynamic voltage active power sensitivity analysis is developed based on the dynamic voltage curve sensitivity analysis which is a method based on the linearization of the system that surrounds a particular tracking and utilizes time-domain simulations, which differs from the P-V curves that are usually used in steady-state voltage stability analysis. This process calculates the sensitivity of the dynamics associated with constraints. Dynamic sensitivity can enumerate fluctuations in system variables in correlation to rapid alterations in system parameters and initial conditions. Computation of these sensitivities-based analyses can be found in [30] and discussed briefly below for completeness.

A power system model can be demonstrated by the following differential-algebraic equations (DAEs) for a systematic voltage stability analysis:

$$\dot{x} = f(x, y; \alpha) \tag{11}$$

$$0 = g(x, y; \alpha) \tag{12}$$

where $x$ represents dynamic variables vector; $y$ denotes algebraic variables vector such as voltage magnitudes and angles of the load bus, and $\alpha$ symbolizes system constraints/parameters.

The paths of (11) and (12) demonstrate the dynamic variables $x$ and algebraic variables $y$ performances, where movements of variables $x$ and $y$ can be expressed as,

$$x(t) = \varphi_x(x_0, t, \alpha) \tag{13}$$

$$y(t) = \varphi_y(y_0, t, \alpha) \tag{14}$$

The Taylor series expansion is implemented in the above equations to acquire the movement sensitivities of $\varphi_x$ and $\varphi_y$ to the original situations and parameter changes, hence

$$\Delta x(t) = \Delta\varphi_x(x_0, t, \alpha) = \frac{\partial \varphi_x(x_0, t, \alpha)}{\partial \alpha}\Delta\alpha = \frac{\partial x(t)}{\partial \alpha}\Delta\alpha \cong x_\alpha(t)\Delta\alpha \tag{15}$$

$$\Delta y(t) = \Delta\varphi_y(y_0, t, \alpha) = \frac{\partial \varphi_y(y_0, t, \alpha)}{\partial \alpha}\Delta\alpha = \frac{\partial y(t)}{\partial \alpha}\Delta\alpha \cong y_\alpha(t)\Delta\alpha \tag{16}$$

The sensitivities of $x_\alpha$ and $y_\alpha$ are computed by using an approximate numeric method, consequently

$$x_\alpha = \frac{\partial x}{\partial \alpha} = \frac{\Delta x}{\Delta \alpha} \approx \frac{\varphi_x(x_0, t, \alpha + \Delta\alpha) - \varphi_x(x_0, t, \alpha)}{\Delta \alpha} \tag{17}$$

$$y_\alpha = \frac{\partial y}{\partial \alpha} = \frac{\Delta y}{\Delta \alpha} \approx \frac{\varphi_y(y_0, t, \alpha + \Delta\alpha) - \varphi_y(y_0, t, \alpha)}{\Delta \alpha} \tag{18}$$

### *3.2 The dynamic voltage-active power sensitivity (DVPS) Formulation and Research Algorithm*

The dynamic sensitivities of (16) and (18) are modified to encounter the main intention of this research. Although the Q-V curve is normally used for voltage stability assessment, however, to have a more straightforward indicator for direct load-shedding decision making, it is more convenient to have an indicator associated with active power (P). Therefore, we proposed the UVLS design by assessing the degree of change in voltage magnitude regarding the degree of change in active power. The variable $y$ represents the bus voltage magnitude and the load shedding amount are denoted by $\alpha$, then the bus voltage variation sensitivities after load shedding on a particular bus are calculated as,

$$\Delta V(t) = \Delta\varphi_V(V_0, t, P) = \frac{\partial \varphi_V(V_0, t, P)}{\partial P}\Delta P = \frac{\partial V(t)}{\partial P}\Delta P \cong V_P(t)\Delta P \tag{19}$$

$$\varphi V_P = \frac{\partial V}{\partial P} = \frac{\Delta V}{\Delta P} \approx \frac{\varphi_V(V_0, t, P + \Delta P) - \varphi_V(V_0, t, P)}{\Delta P} \tag{20}$$

The dynamic sensitivities are calculated to obtain the location of load shedding as well. A dynamic voltage-active power sensitivity (DVPS) is formulated to provide information about the participation of bus *j* after load shedding on bus *j* with a predefined amount to the enhancement of the system voltage stability. The premeditated sensitivity is $\left[\partial V_i / \partial P_j\right]$, which expresses the degree of voltage magnitude variations on the bus *i* with the changes in load shedding amount on bus *j*. The DVPS on bus *j* is calculated by curtailing active power on bus *j* by a small quantity then evaluates its effect on all critical buses voltage magnitudes along with time domain, hence the DVPS is formulated as,

$$DVPS_j = \sum_{i=1}^{n_k}\left[\sum_{t=0}^{t_s}\left[\frac{\partial V_i}{\partial P_j}\right]_{t=t_k}\right] \tag{21}$$

$$\partial P_j = \Delta P_j = P_{shed_j}$$

Where $t_k$ is the instantaneous time which is the time instant throughout the time domain simulation where the sensitivity value $\left[\partial V_i/\partial P_j\right]$ is recorded to calculate DVPS and $t_s$ is the number of instantaneous time which is the total of all the time instant where $\left[\partial V_i/\partial P_j\right]$ is recorded.

The bus with the highest DVPS has the predominant influence in improving the system voltage stability on the critical buses based on time-domain analysis, therefore this bus is chosen as a candidate for load shedding location. For better understanding, the stages for determination of the amount and location of load shedding are illustrated through the flowchart in Fig. 4 whereas the computational procedures are explained in detail below:

*Step 1* Set of the load shedding quantity. In this research, the load shedding quantity is arranged at 1 % of the total load for each iteration.

*Step 2* Determination of a predefined set of contingencies, then selects a fault.

*Step 3* Execution of dynamic voltage stability analysis or time-domain simulation analysis to examine the voltage behavior for all buses in case of unforeseen circumstances. In this stage, the post-fault voltage recovery on all buses is checked whether they are within the stability limit. If so, the process terminates. Otherwise, it indicates that the system needs load shedding to avoid possible voltage collapse, then go to *Step 4*.

*Step 4* Identification of critical buses and regions. The critical region is the region where neighboring buses experience voltage drop below the stability limit and they have similar voltage drop trajectory.

*Step 5* Calculation of DVPS using Eq. (21) to evaluate the influence of each load bus in the voltage stability recovery of the buses within the critical areas with load shedding quantity of 1% of the total load. The bus with the highest DVPS means that this bus is the most sensitive bus therefore it has the main influence on increasing the voltage magnitude with a small amount of load shedding. The location of load shedding is determined based on the highest DVPS value.

*Step 6* Application of load shedding on the designated bus with the highest DVPS.

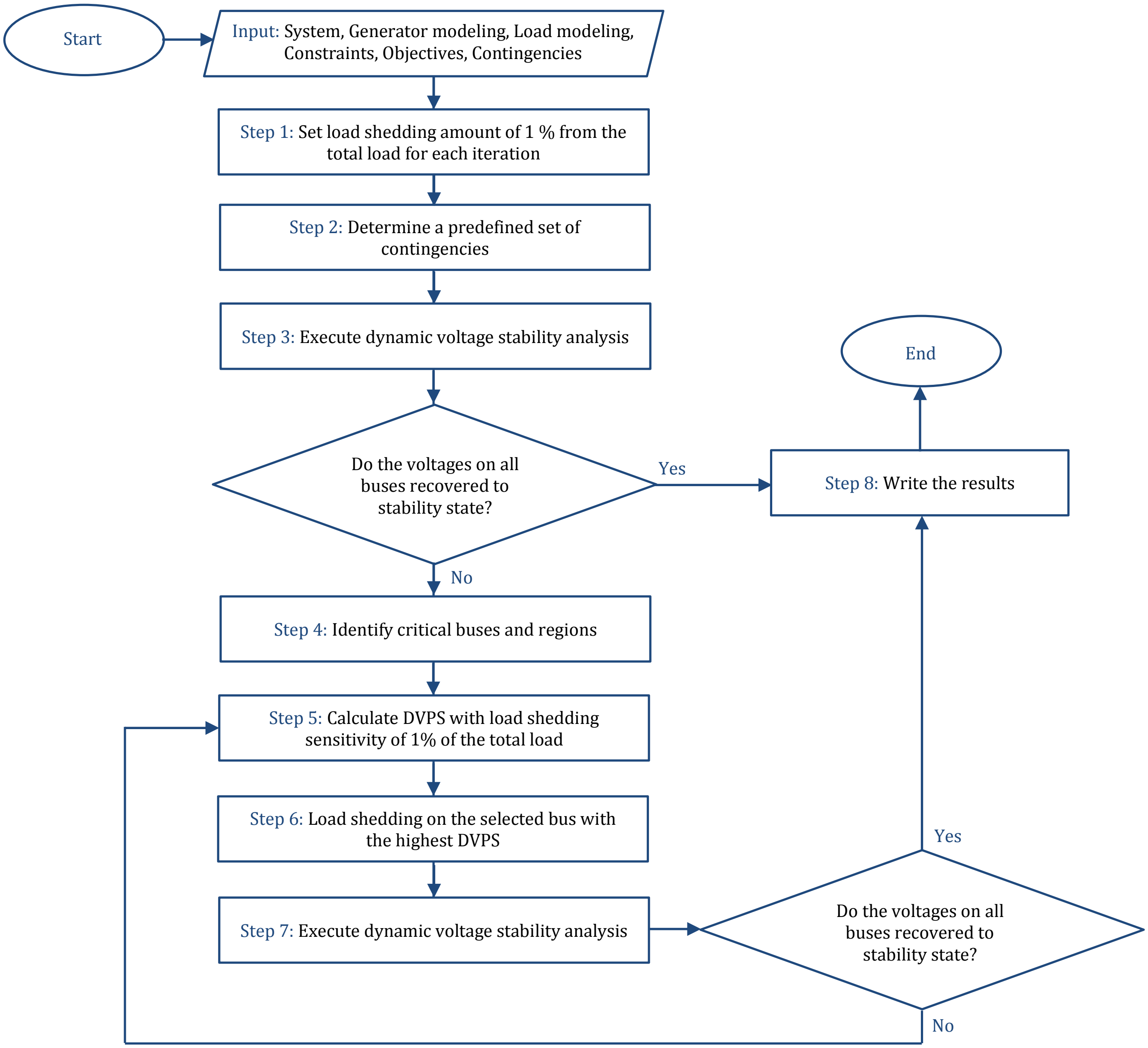


Fig. 4 Flowchart of the proposed UVLS scheme

*Step 7* Execution of dynamic voltage stability analysis to assess system operation after load shedding. At this point, further examinations are carried out to identify whether the post-fault voltage recovery performance on all load buses after load shedding satisfies the voltage stability constraints. If yes, the workflow proceeds to *Step 8* to conclude the process and write the results. Else, it indicates more load shedding, hence the framework switches to *Step 5*.

*Step 8* Completion of dynamic UVLS scheme process, write the results and stop the process.

### *3.4 Stability Constraints, Optimization Objective, and Voltage Stability Margin*

In order to meet the voltage stability criteria, the following voltage stability constraints are used:

$$0.9 \leq V_{(t_{k+N})} \leq 1.1 \tag{22}$$

Furthermore, the optimization objective of the dynamic curve sensitivity UVLS is to determine the minimum quantity of load shedding to ensure voltage constraints are met, then

$$\min \sum_{j=i}^{m} P_{shed_j} \tag{23}$$

where $m$ is the number of load shedding locations.

The voltage stability margin (VSM) is computed by using the PV curve methods [5]. VSM is stated as the growth of the total load in the region of load addition which is calculated from the base case state to the maximum power transfer (PV curve nose point) signified in MW or percentage. The VSM can be computed with this relation

$$VSM\ (\%) = \frac{\lambda_k^{max} - \lambda_{base}}{\lambda_k^{max}} \text{ x } 100\% \tag{24}$$

where $\lambda_{base}$ is the basic loading parameter for basic case operations and $\lambda_k^{max}$ is the maximum loading parameter for particular circumstances.

## 4. The Test System: South Sulawesi Power System

### *4.1 Overview of the Study System [31]*

The South Sulawesi interconnection power system comprises various power plants interconnected by several high voltage transmission lines with the provincial capital of Makassar City. The South Sulawesi system has a typical feature where the main cost-effective power plants are positioned in the north of the system, whereas the major load center is found in the south. The total power generation in the northern part of the system is 384.9 MW whereas the total generation in the southern part is 232.7 MW. The Total peak load of the system for the case study was 556.5

MW.

The load in the South Sulawesi system is dominated by the residential load. As a center of provincial government and business, the load in Makassar City (which is the capital of the South Sulawesi province, business center for eastern Indonesia represented by buses 10, 11, 12, and 13) is dominated by dynamic loads which are commonly air conditioner and water pump loads. In addition, two large cement industries are connected to bus 8. Fig. 5 presents the single-line diagram of the case study system.

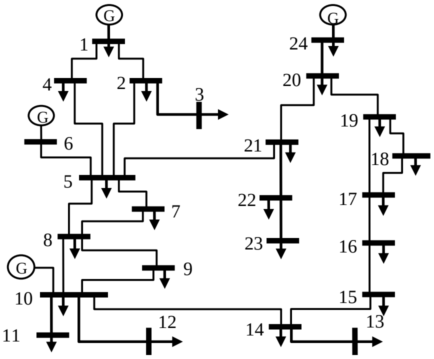


Fig. 5 The single-line diagram of the case study [31]

### *4.2 Load Composition*

In this study, the load is presumed to be peak load. In the provincial capital, Makassar, (buses 10, 11, 12, and 13), the load is represented as 50% static load and 50% dynamic load, because Makassar is the province’s business center and its residents are generally in the middle and upper economic levels. Fig. 6 shows the assumption of the load illustration in Makassar. On other buses, the load is considered as 80% static load and 20% dynamic load, with an exception, on bus 8, where there are two large cement industries connected, the load is depicted as 30% static load and 70% dynamic load. Detail of the system load composition and parameters of induction motors [23] are presented respectively in Table I and Table II.

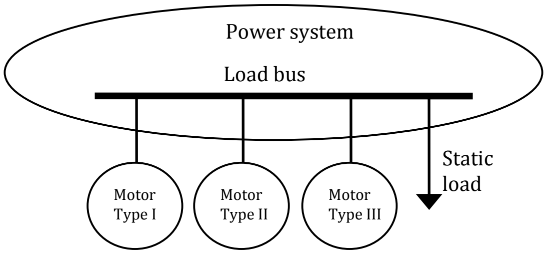


Fig. 6 Assumption of a schematic representation of load at Makassar City region

TABLE I LOAD COMPOSITION

| Bus No | Load type (%) | | | | |
|---|---|---|---|---|---|
| | Static | Dynamic motor | | | |
| | | I | II | III | IV |
| 1 – 7, 9, 14-24 | 80 | 20 | - | - | - |
| 8 | 30 | 20 | - | - | 50 |
| 10 - 13 | 50 | 20 | 25 | 5 | - |

TABLE II INDUCTION MOTOR PARAMETERS [23]

| Motor type | I | II | III | IV |
|---|---|---|---|---|
| Stator resistance - $R_s$ | 0.077 | 0.064 | 0.013 | 0.013 |
| Stator leakage reactance – $X_s$ | 0.107 | 0.091 | 0.14 | 0.067 |
| Magnetizing reactance - $X_m$ | 2.22 | 2.23 | 2.4 | 3.8 |
| Rotor resistance - $R_r$ | 0.079 | 0.059 | 0.009 | 0.009 |
| Rotor leakage resistance - $X_r$ | 0.098 | 0.071 | 0.12 | 0.17 |
| Rotor inertia constant - $H$ | 0.74 | 0.34 | 0.8 | 1.5 |
| Load factor | 0.46 | 0.8 | 0.7 | 0.8 |

| Where | | |
|---|---|---|
| | Type I | Weighted cumulative of residential motors |
| | Type II | Weighted cumulative of air conditioning dominant motors |
| | Type III | Water pump |
| | Type IV | Large industrial induction motors |

## 5. Case Study and Analysis

Since the total load is 556.5 MW, therefore the load shedding amount for each DVPS computation is set at 1% or about 5 MW. The case observed in this case study was an outage between buses 8 and 10 since it resulted in a severe voltage collapse situation.

Fig. 7 shows the voltage collapse after a disturbance has occurred which causes the loss of the transmission line between buses 8 and 10. Because of this outage, there are 3 unstable regions detected: Makassar City region (buses 10 - 14), buses 8 and 9; and buses 22 and 23 where the voltage collapse in these regions are shown in Figs. 8, 9, and 10 respectively. Specifically from Fig. 8, this clearly illustrates a substantial voltages drop in the Makassar substations which drop to the voltage of 0.66 – 0.69 p.u. at time *t*=30 s. This is because Makassar as the load center in the South Sulawesi system has a significantly large quantity of dynamic induction motor loads. Because induction motors have trouble accelerating after big perturbance then they stall and distress the voltage in the Makassar region.

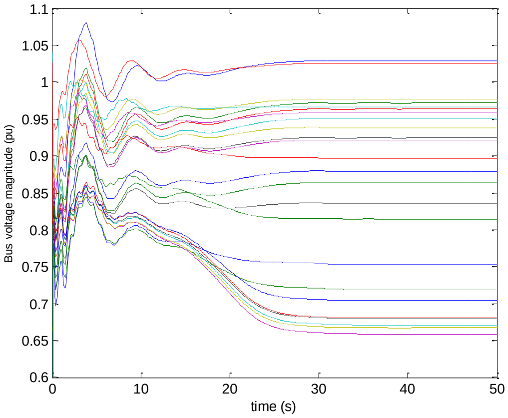


Fig. 7 Voltage declines in all buses after interruptions between buses 8 and 10

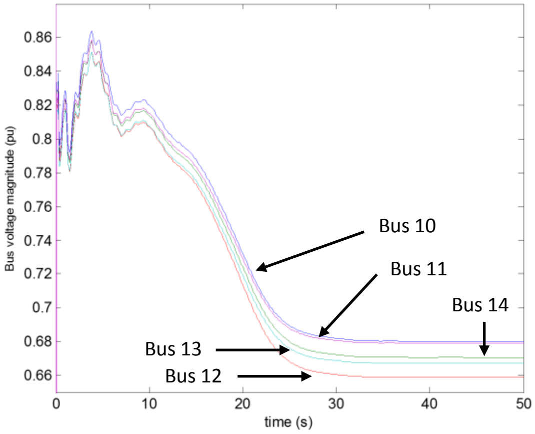


Fig. 8 Voltage declines in buses 10 – 14 after interruptions between buses 8 and 10

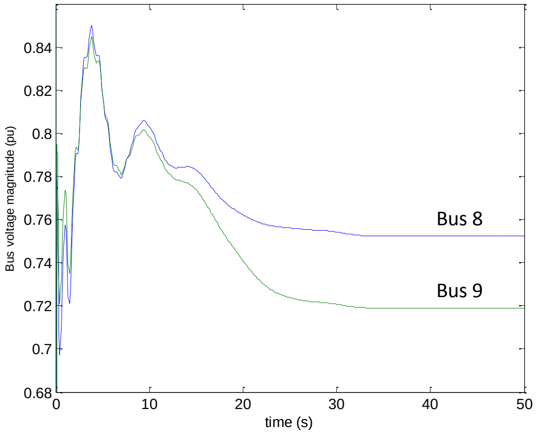


Fig. 9 Voltage declines in buses 8 and 9 after interruptions between buses 8 and 10

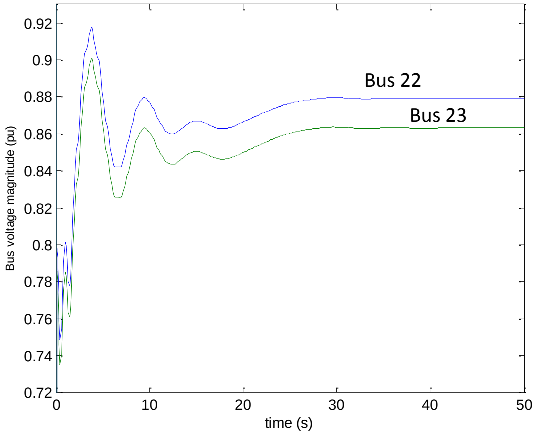


Fig. 10 Voltage declines in buses 22 and 23 after interruptions between buses 8 and 10

In this simulation, the voltage stability constraint is violated, therefore load shedding is required to retrieve stability. Dynamic sensitivity analysis is carried out to evaluate the impact of 5 MW load shedding on each load bus in the critical unstable region. For illustration, we took bus 13 and 3 as examples to calculate the DVPS value. Since there are 9 unstable buses (buses 8, 9, 10, 11, 12, 13, 14, 22, and 23), hence we only analyzed the sensitivity of 5 MW load shedding on those unstable buses. Fig. 11 and Fig. 12 illustrate the sensitivities of the dynamic voltage curve of the mentioned unstable buses for the first iteration of 5 MW load shedding is applied to bus 13 and bus 3, respectively. It can be concluded from both figures, that the sensitivity of the dynamic voltage curve for the 5 MW load shedding on bus 13 is better than the dynamic voltage curve sensitivity for the 5 MW load shedding on bus 3. Furthermore, DVPS as defined in Eq. (21) is computed to present a distinctive indicator for the location of load shedding. The results of calculation $\sum_{t=0}^{t_s}\left[\frac{\partial V_i}{\partial P_j}\right]_{t=t_k}$ with respect to all unstable buses to calculate DVPS on buses 13 and 3 are shown in Table III. The DVPS values for buses 13 and 3 are calculated based on the sensitivities in Fig. 11 and Fig. 12, respectively. In calculating the DVPS values, we used a time interval of 0.5 seconds for a period of 0 – 10 seconds and 1 second for 10 – 30 seconds. As can be seen in Fig. 7., the voltages fluctuate a lot during the first 10 seconds after the disturbance, change slightly over 10-30 seconds, and tend to remain the same after 30 seconds.

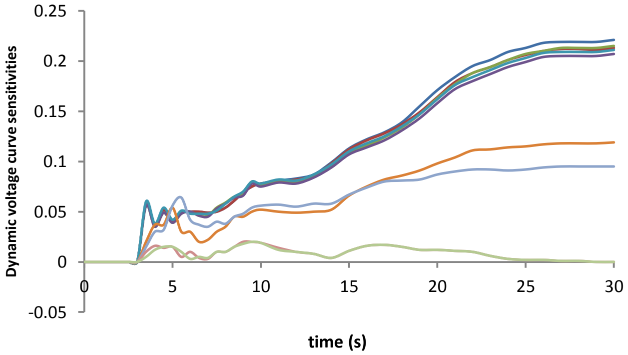


Fig. 11 Dynamic voltage curve sensitivities if a 5 MW load shedding is applied to bus 13

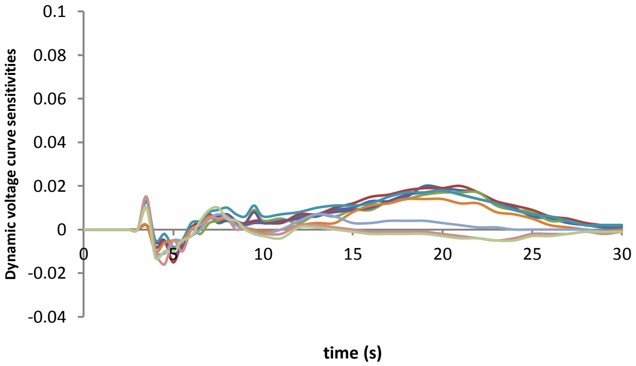


Fig. 12 Dynamic voltage curve sensitivities if a 5 MW load shedding is applied to bus 3

TABLE III DVPS CALCULATION

| | $\sum_{t=0}^{t_s}\left[\frac{\partial V_i}{\partial P_j}\right]_{t=t_k}$ | |
|---|---|---|
| Bus *j* | 13 | 3 |
| Bus *i* | | |
| 8 | 2.222 | 0.038 |
| 9 | 2.352 | 0.125 |
| 10 | 3.933 | 0.257 |
| 11 | 3.934 | 0.184 |
| 12 | 4.051 | 0.187 |
| 13 | 3.957 | 0.22 |
| 14 | 3.829 | 0.188 |
| 22 | 0.314 | -0.047 |
| 23 | 0.326 | -0.041 |
| DVPS Value | 24.918 | 1.111 |

Fig. 13 informs the DVPS value in the first iteration for 5 MW sensitivity in each load bus. As the result, bus 13 has the highest DVPS value (24.92) and it is indicated with a red bar. Load curtailment of 5 MW is evaluated on bus 13 and the system voltage performance is re-assessed. In this phase, the system voltage is not able to improve back to its stability condition, hence the dynamic voltage curve sensitivities are executed again to compute DVPS. For this outage, this process was done in 6 iterations until the constraints are met and the results of DVPS value in each iteration are given in Table IV. Table V summarizes the highest DVPS value for each iteration and the buses with the highest DVPS for each iteration. Therefore, we obtained the load shedding locations for this case are buses 13 (15 MW), 9 (5 MW), and 23 (10 MW) and are summarized in Table VI. Fig. 14 shows the results of the voltage enhancement after load curtailment with a total of 30 MW on buses 13, 9 and 23. This verifies that all voltages have significantly improved and the system stability has been retrieved.

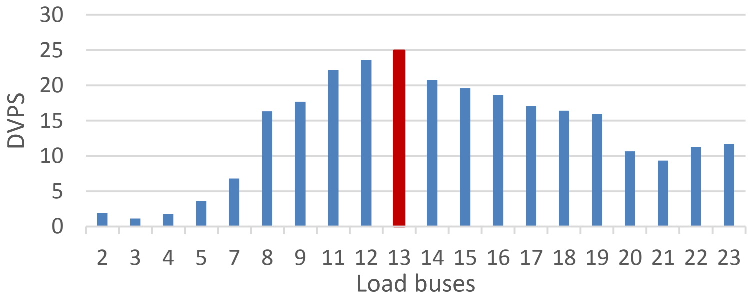


Fig. 13 DVPS value in the first iteration

TABLE IV DVPS VALUE

| | DVPS | | | | | |
|---|---|---|---|---|---|---|
| Iteration | I | II | III | IV | V | VI |
| Bus No | | | | | | |
| 2 | 1.91 | 1.24 | 1.03 | 0.87 | 0.77 | 0.53 |
| 3 | 1.11 | 0.97 | 0.78 | 0.57 | 0.46 | 0.32 |
| 4 | 1.76 | 1.12 | 0.98 | 0.76 | 0.65 | 0.44 |
| 5 | 3.56 | 2.79 | 2.11 | 1.95 | 1.76 | 1.32 |
| 7 | 6.79 | 5.35 | 4.05 | 3.34 | 2.56 | 1.06 |
| 8 | 16.34 | 14.11 | 13.33 | 9.12 | 6.34 | 5.12 |
| 9 | 17.66 | 15.23 | **14.12** | 9.88 | 5.65 | 5.45 |
| 11 | 22.17 | 18.98 | 12.56 | 9.69 | 1.78 | 1.56 |
| 12 | 23.57 | 20.04 | 13.02 | 10.03 | 1.89 | 1.32 |
| 13 | **24.92** | **21.32** | 13.78 | **10.65** | 1.12 | 0.95 |
| 14 | 20.76 | 17.64 | 11.45 | 9.34 | 1.67 | 0.65 |
| 15 | 19.57 | 15.87 | 10.87 | 8.67 | 3.76 | 2.89 |
| 16 | 18.63 | 13.96 | 9.98 | 7.67 | 4.78 | 3.23 |
| 17 | 17.05 | 12.31 | 9.02 | 6.99 | 4.03 | 3.54 |
| 18 | 16.4 | 11.44 | 8.34 | 6.12 | 5.78 | 3.97 |
| 19 | 15.89 | 9.98 | 7.86 | 5.46 | 4.78 | 3.89 |
| 20 | 10.67 | 7.02 | 5.79 | 4.67 | 3.78 | 3.08 |
| 21 | 9.34 | 5.95 | 4.57 | 3.56 | 2.88 | 2.01 |
| 22 | 11.23 | 10.28 | 8.79 | 8.12 | 7.65 | 6.45 |
| 23 | 11.68 | 10.57 | 9.86 | 9.55 | **8.78** | **8.12** |

TABLE V HIGHEST DVPS VALUE AND LOAD SHEDDING LOCATION FOR EACH ITERATION

| Iteration | Highest DVPS | Bus (location) |
|---|---|---|
| I | 24.92 | 13 |
| II | 21.32 | 13 |
| III | 14.12 | 9 |
| IV | 10.65 | 13 |
| V | 8.78 | 23 |
| VI | 8.12 | 23 |

TABLE VI LOAD SHEDDING LOCATIONS

| Location | Amount (MW) |
|---|---|
| 13 | 15 |
| 9 | 5 |
| 23 | 10 |

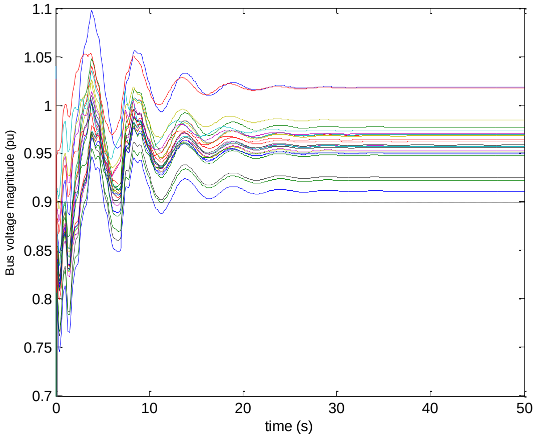


Fig. 14 Voltage improvement after 30 MW load shedding on buses 13, 9 and 23

To illustrate the advantage of the proposed scheme, this work observes how the voltage improvement if the load shedding is carried out on bus 13 itself for 30 MW as a comparison because in the first iteration bus 13 has the highest DVPS value. Fig. 15 shows the voltage behavior after 30 MW load shedding on bus 13. It is interesting, even though the voltage magnitude increase but the voltage on buses 8 and 23 cannot return to the stability constraints. Therefore, it is not recommended to shed load on bus 13 by 30 MW, although in the first iteration, bus 13 has the highest DVPS. By assessing the load shedding locations by a smaller amount, can provide a more efficient load shedding scheme.

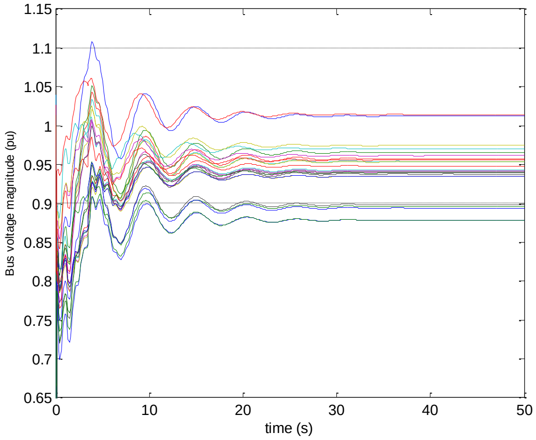


Fig. 15 Voltage performance after 30 MW load curtailment on bus 13

Furthermore, this work also investigates and compares the proposed load shedding with the South Sulawesi system load shedding scheme. The state electricity provider had a load shedding design with total load shedding of 31.64 MW and was located on buses 19, 22, 4, 2, 3, 24, and 18 as shown in Table VII [31]. Fig. 16 shows the voltage behavior after load shedding on these buses and confirms that with this arrangement, the system voltage stability cannot recover back to the stability constraints. It can be seen that after the load curtailment, the system voltage can slightly increase, but after *t*=40 s, the voltages in the Makassar region drop significantly to approximately 0.66 p.u. This condition is the same as if there was no load shedding. Therefore, this load shedding scheme is not as effective and efficient as our proposed scheme. Consequently, more load shedding amount is required in order to comply with the system voltage stability constraints and it is not recommended to perform load shedding on these buses. Table VIII presents a comparison between the results of our proposed methodology and the South Sulawesi system scheme.

TABLE VII THE SOUTH SULAWESI SYSTEM LOAD SHEDDING SCHEME [31]

| No | Substation | Load shedding amount (MW) |
|---|---|---|
| 1 | 19 | 4.44 |
| 2 | 22 | 4.5 |
| 3 | 4 | 4.38 |
| 4 | 2 | 3.27 |
| 5 | 3 | 1.53 |
| 6 | 24 | 10.38 |
| 7 | 18 | 3.15 |
| Total load shedding (MW) | | 31.64 |

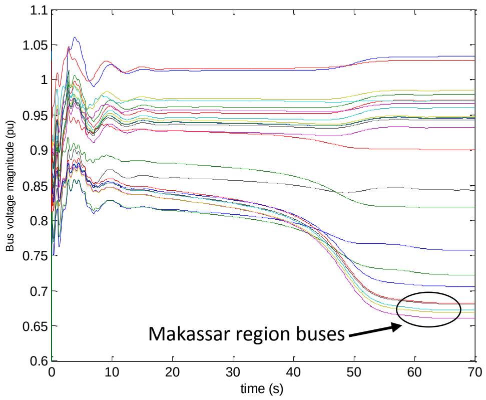


Fig. 16 Voltage performance after load shedding based on the South Sulawesi system scheme

TABLE VIII COMPARISON BETWEEN PROPOSED METHOD AND THE SOUTH SULAWESI SCHEME

| Scheme | Load shedding | | Remarks |
|---|---|---|---|
| | Location | Total (MW) | |
| Proposed method | 13, 9, 23 | 30 | Stable |
| South Sulawesi scheme (Table VI) | 19, 22, 4, 2, 3, 24, 18 | 31.64 | Not stable |

The VSM is assessed on the most critical bus after an outage which is bus 12. From Fig. 8, this bus has the lowest voltage magnitude. The base load on bus 12 is 119.2 MW. Fig. 17 shows bus 12 PV curve for the pre-contingency condition with $\lambda^{max}$ of 1.37 which gives 27% VSM. The complete VSM calculation for all other conditions can be seen in Table IX. From Table IX, the VSM for the post-contingency condition is only -4.17%. The negative value of VSM indicates the system instability, therefore precautions are required to preclude the system from voltage collapse. In addition, Table VIII also presents the VSM values for after load shedding conditions. As shown in Fig. 14, the system voltage can improve back to a stable situation after load shedding on the buses based on the proposed method. This is clarified with a positive VSM value of 11.86%. Whereas Fig. 16 shows the system still unstable after load shedding based on the existing scheme from the utility and the VSM is also negative (-2.04%). From this, we can see the results of the VSM calculations are consistent with the dynamic simulation results to prove the robustness of the proposed DVPS based UVLS scheme.

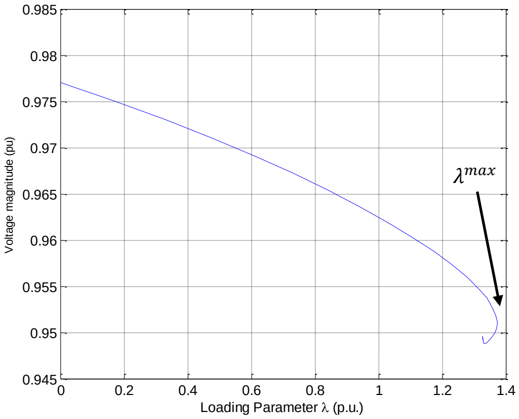


Fig. 17 Pre-contingency PV curve of bus 12

TABLE IX VOLTAGE STABILITY MARGIN

| Condition | $\lambda^{max}$ | VSM (%) |
|---|---|---|
| Pre-contingency | 1.37 | 27 |
| Post-contingency | 0.96 | -4.17 |
| Proposed method | 1.11 | 11.86 |
| South Sulawesi scheme | 0.98 | -2.04 |

## 6. Conclusions

This paper recommends a novel under-voltage load shedding design to stabilize the system after large perturbance and to ensure the system secure constraints are fulfilled. The UVLS scheme is designed based on the dynamic sensitivities method that calculates dynamics sensitivity related to system constraints and provides a technique of calculating variations in the system variables with respect to rapid changes in system initial conditions and parameters. In this work, dynamic sensitivity is utilized to verify the minimum amount of load curtailment and to decide the location of load curtailment.

This paper uses the South Sulawesi power system in Indonesia as a case study. The calculation of the dynamic sensitivity index has indicated different buses as load shedding location. The dynamic simulation results as well as the calculations of the voltage stability margin confirm the robustness of the proposed method compared to the load shedding scheme used by the South Sulawesi power system. The dynamic sensitivity index gives convenient information for finding the most appropriate location for load shedding. Finally, it is worth to be clarified that the proposed UVLS methodology consists of a broad method and procedure that can be implemented in designing a more realistic, reliable, and effective approach to dynamic UVLS that takes into account the modeling of loads to any power system. Proper load modeling will give a significant impact on the accuracy of the simulation results.

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## Figure Legends

Fig. 1 The IEEE 14 Bus Reliability Test System

Fig. 2 Voltage performance after disturbance and load shedding

Fig. 3 Schematic circuit of the composite load model [27]

Fig. 4 Flowchart of the proposed UVLS scheme

Fig. 5 The single line diagram of the case study [31]

Fig. 6 Assumption of schematic representation of load at Makassar City region

Fig. 7 Voltage declines in all buses after interruptions between buses 8 and 10

Fig. 8 Voltage declines in buses 10 – 14 after interruptions between buses 8 and 10

Fig. 9 Voltage declines in buses 8 and 9 after interruptions between buses 8 and 10

Fig. 10 Voltage declines in buses 22 and 23 after interruptions between buses 8 and 10

Fig. 11 Dynamic voltage curve sensitivities if a 5 MW load shedding is applied to bus 13

Fig. 12 Dynamic voltage curve sensitivities if a 5 MW load shedding is applied to bus 3

Fig. 13 DVPS value in the first iteration

Fig. 14 Voltage improvement after 30 MW load shedding on buses 13, 9 and 23

Fig. 15 Voltage performance after 30 MW load curtailment on bus 13

Fig. 16 Voltage performance after load shedding based on the South Sulawesi system scheme

Fig. 17 Pre-contingency PV curve of bus 12

## Table Legends

| | |
|---|---|
| Table I | Load Composition |
| Table II | Induction Motor Parameters [23] |
| Table VIII | DVPS Calculation |
| Table IX | DVPS Value |
| Table V | Highest DVPS Value and Load Shedding Location for each iteration |
| Table XI | Load Shedding Locations |
| Table XII | The South Sulawesi System Load Shedding Scheme [31] |
| Table XIII | Comparison between Proposed Method and The South Sulawesi Scheme |
| Table IX | Voltage Stability Margin |

*The authors would like to thank the Editor and Reviewers. All the comments have been incorporated in the paper appropriately and below are the response to the reviewers' comments.*

Reviewers' comments:

Reviewer #1: The manuscript is interesting and well organized, even though it might still benefit from a more thorough English language revision.

*The paper has had an English proofreading.*

The reviewer has some questions that might need to be addressed before the manuscript is considered fit for publication:

1. Is a 1% (5 MW?) load shedding resolution a realistic per bus value? Would it apply on other kinds of systems? Authors should state it if so and address the possible impact of larger/smaller or mixed sized steps.

*Yes, the load shedding value of 1% is realistic. As we can see from Table VII, the electricity provider for the South Sulawesi electricity system also implements a load shedding of around 1% for certain buses, even for some buses, the value is less than 1%. We have added more explanation on page 8, line 3 as follow:*
*The amount of load shedding 1% for each iteration is considered sufficient to calculate the total amount of load shedding. However, it is possible to reduce the amount of load shedding per iteration. A more optimal amount of total load shedding can be obtained but more iterations are required. On the other hand, increasing the amount of load shedding per iteration will result in the possibility of a more calculated amount of load shedding than is needed (over shedding). This method can be applied in any power system.*

2. Authors do not explain why "The deficiency of dynamic load modeling in the time domain simulation is assumed to be the main reason for the inconsistencies between real measurements and simulation outcomes." Maybe stating some of the references?...

*Thank you, it is based on the study from "IEEE Task Force on Load Representation for Dynamic Performance, "Standard Load Models for Power Flow and Dynamic Performance Simulation," IEEE Transactions on Power Systems, vol. 10, pp. 1302-1313, 1995" which we have included in the references number [23].*

3. Authors state that "Moreover, the proper load modeling will give significant impact on the accuracy of the simulation results." This seems to be a conclusion/result of the analysis presented in manuscript, but appears in the Introduction

*Thank you for your comment. We have moved the mentioned sentence to conclusions, page 26, the last line of conclusions.*

4. Slip (s) is mentioned but not visible in Fig 1.

*It should have included the slip, but the slip writing was not visible after I made the image smaller. Therefore, I have enlarged Fig. 1 (page 10) and the image has shown the slip (s).*

5. The "dynamic" (UVLS) in the title and most of the document, refers to the analysis of the behavior of the system and its loads, or to the iterative nature of the method? (Or both…)

*The "dynamic" (UVLS) refers to that UVLS is designed using dynamic voltage stability analysis and considering dynamic load modeling as well.*

6. First text paragraph on page 18 is quite confusing. Does it mean to exemplify the advantages of the iterative method proposed?

*Yes, this paragraph tries to illustrate the advantages of shedding smaller quantities at different locations compared to shedding larger quantities (total) directly on one bus. Although the total amount of load shedding is the same, the voltage improvement is different. Therefore, we have edited this paragraph on page 23 to avoid any further confusion as follow:*
*To illustrate the advantage of the proposed scheme, this work observes how the voltage improvement if the load shedding is carried out on bus 13 itself for 30 MW as a comparison because in the first iteration bus 13 has the highest DVPS value. Fig. 15 shows the voltage behavior after 30 MW load shedding on bus 13. It is interesting, even though the voltage magnitude increase but the voltage on buses 8 and 23 cannot return to the stability constraints. Therefore, it is not recommended to shed load on bus 13 by 30 MW, although in the first iteration, bus 13 has the highest DVPS. By assessing the load shedding locations by a smaller amount, can provide a more efficient load shedding scheme.*

7. Authors compare their proposal with the utility load shedding scheme but appear to give no description whatsoever of this "utility scheme". The comparison is thus a bit "opaque".

*Utility in this paper refers to the electricity provider for the South Sulawesi power system or the Indonesian State Electricity Company (PT. PLN (Persero) in Indonesian). Therefore, we have changed the term "utility scheme" in this paper is changed to "South Sulawesi system load shedding scheme" as in Table VII (page 24).*

**Reviewer #3: Major comments**

1. Is this an UVLS for off-line only computations or it can be used for real-time on-line protection schemes? In the former case the results can be used to predetermine a set of contingencies only and apply UVLS in specific buses. In the latter case how you would incorporate it in an on-line scheme?

*The calculations for the UVLS design are done off-line and the results can then be applied to real-time online protection through an automatic load shedding scheme that is incorporated into the SCADA system with coordination between the system planners and protection engineers. System planners can conduct this study to calculate the amount of load to be removed and select load shedding locations based on each contingency defined to create a UVLS setting table. The results of the study of the system planner with various scenarios can then provide assistance to the protection engineer in selecting the appropriate arrangement for the assigned under-voltage relays. The under-voltage relays must be properly designed to differentiate between situations needing load shedding and situations which do not need load shedding. They then can incorporate the planned UVLS setup into the SCADA system with the IF-THEN rule algorithm and create automated UVLS for online. By having an automatic UVLS fed into the SCADA system, the proper load shedding action can react immediately rather than taking the time to make choices once a real event occurs.*

2. Please make clear the meaning of instantaneous time and number of instantaneous time.

*We have added the meaning of instantaneous time and number of instantaneous time on page 13, line 1 as follow:*
*The instantaneous time is the time instant throughout the time-domain simulation where the sensitivity value* $\left[\partial V_i/\partial P_j\right]$ *is recorded to calculate DVPS and the number of instantaneous time is the total of all the time instant where* $\left[\partial V_i/\partial P_j\right]$ *is recorded.*

3. I assume the calculation of DVPS starts when the Voltage Stability Margin becomes negative.

*The DVPS calculation starts when the voltage at any load bus drops below the stability limit.*

4. In the case study, you write that the interval for the sensitivity calculations is 0.5 sec for the period 0-10 sec and 1 sec for the period between 10-30sec. This 30 second period where does it refer? I assume for the calculation of DVPI in each iteration?

*As can be seen in Fig. 7., the voltages fluctuate a lot during the first 10 seconds after the disturbance, change slightly over 10-30 seconds, and tend to remain the same after 30 seconds. That is why we only took a 0-30 seconds period for the DVPS calculation.*

5. Clarify the connection between Figures 9 and 10 Table III.

*We have clarified the connection between Fig. 9, Fig. 10, and Table III. Since we have additional figures, hence Fig. 9 now becomes Fig. 11, and Fig. 10 becomes Fig. 12. The explanations are on pages 19-20 as follow:*

*In this simulation, the voltage stability constraint is violated, therefore load shedding is required to retrieve stability. Dynamic sensitivity analysis is carried out to evaluate the impact of 5 MW load shedding on each load bus in the critical unstable region. For illustration, we took bus 13 and 3 as examples to calculate the DVPS value. Since there are 9 unstable buses (buses 8, 9, 10, 11, 12, 13, 14, 22, and 23), hence we only analyzed the sensitivity of 5 MW load shedding on those unstable buses. Fig. 11 and Fig. 12 illustrate the sensitivities of the dynamic voltage curve of the mentioned unstable buses for the first iteration of 5 MW load shedding is applied to bus 13 and bus 3, respectively. It can be concluded from both figures, that the sensitivity of dynamic voltage curve for the 5 MW load shedding on bus 13 is better than the dynamic voltage curve sensitivity for the 5 MW load shedding on bus 3. Furthermore, DVPS as defined in Eq. (21) is computed to present a distinctive indicator for the location of load shedding. The results of calculation* $\sum_{t=0}^{t_s}\left[\frac{\partial V_i}{\partial P_j}\right]_{t=t_k}$ *in respect to all unstable buses to calculate DVPS on buses 13 and 3 are shown in Table III. The DVPS values for buses 13 and 3 are calculated based on the sensitivity in Fig. 11 and Fig. 12, respectively. In calculating the DVPS values, we used a time interval of 0.5 seconds for a period of 0 – 10 seconds and 1 second for 10 – 30 seconds. As can be seen in Fig. 7., the voltages fluctuate a lot during the first 10 seconds after the disturbance, change slightly over 10-30 seconds, and tend to remain the same after 30 seconds.*

6. Please provide a more clear figure with the sequence of events with fewer buses and distinctive stages, i.e.disturbance, load sheding.

*We have provided an explanation in Section 1.1, page 4 as follow:*

*Research and experience have proven that UVLS is an excellent countermeasure against voltage instability. In this part, we will provide a brief overview of UVLS using the IEEE 14 bus Reliability Test System as shown in Fig. 1 as an example. It is assumed that there is an outage between bus 6 and bus 13. Figs. 2 (a) and (b) show the voltage drop after the fault across all buses and the critical buses, respectively. Then Fig. 2 (c) demonstrates the voltage recovery after load shedding.*

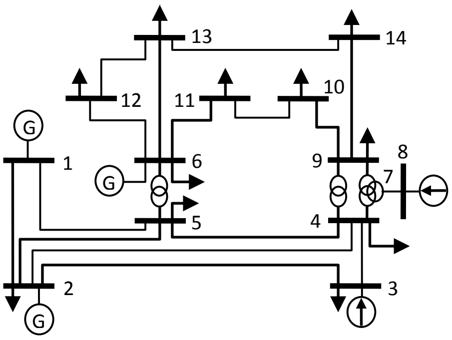
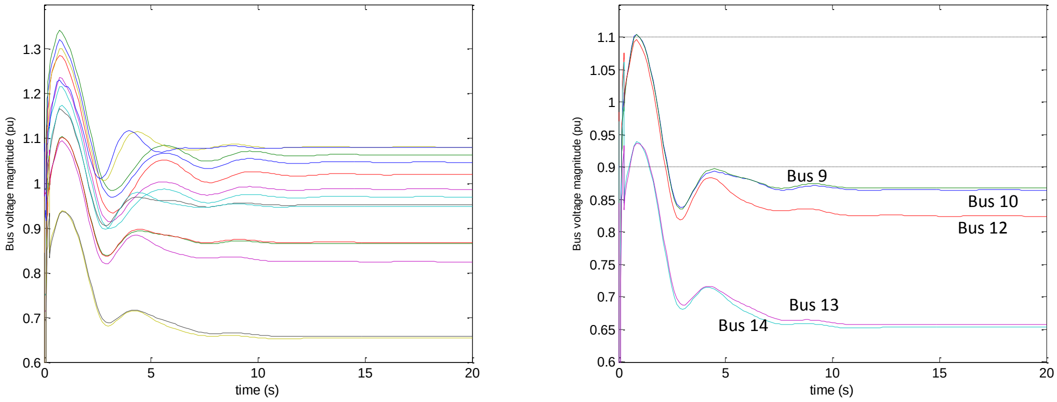
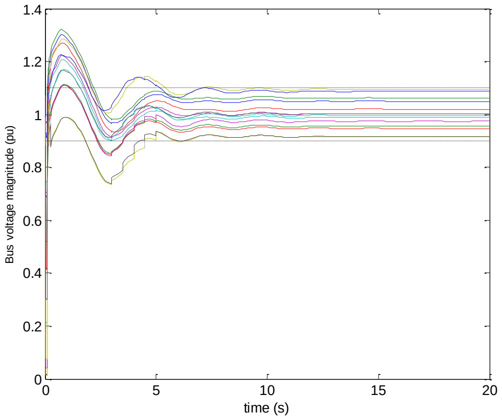


Fig. 1 The IEEE 14 Bus Reliability Test System



(a) Voltage drop at all buses (b) Voltage drop at the critical buses



(c) Voltage recovery after load shedding

Fig. 2 Voltage performance after disturbance and load shedding

7. In Table IV, for the 4th iteration I see that the DVPS for bus 13 (10.65) is larger than for bus 9 (9.88). Why do you shed load from 9? There is an upper limit in the load shedding?

*Because in the 3rd iteration, bus 9 has the highest DVPS value. To clarify, I have added a new Table V on page 22 that summarizes the highest DVPS value for each iteration and which bus has the highest DVPS.*

TABLE V HIGHEST DVPS VALUE AND LOAD SHEDDING LOCATION FOR EACH ITERATION

| Iteration | Highest DVPS | Bus (location) |
|---|---|---|
| I | 24.92 | 13 |
| II | 21.32 | 13 |
| III | 14.12 | 9 |
| IV | 10.65 | 13 |
| V | 8.78 | 23 |
| VI | 8.12 | 23 |

TABLE II LOAD SHEDDING LOCATIONS

| Location | Amount (MW) |
|---|---|
| 13 | 15 |
| 9 | 5 |
| 23 | 10 |

**Minor comments**

1. In page 6, 1st paragraph, last sentence please revisit, i.e. remove "hence" or rephrase.
2. Section 1, last paragraph, please change roman numerals for sections with numbers. Also replace any other reference.
3. In subsection 2.2, second line, replace "analysis including in the UVLS design" with "analysis included in the UVLS design".
4. Paragraph 2.2.1, first sentence, "loads are content on the voltage of a bus" must become "loads depend on the voltage of a bus". Also remove the second or at the end of the sentence, it is polynomial equations.
5. Page 10, third line from the bottom, "executed" should become "calculated".
6. Page 11, first line, "notifies" should become "express".
7. Page 12, Step 1, I think you should change "Calculation" with "Set".
8. Subsection 4.2, "static load and 20% dynamic load. In exception, on bus 8" should become "static load and 20% dynamic load, with an exception, on bus 8".
9. Page 15, section 5., second paragraph, "Figs 6, 7 and 8 correspondingly" should become "Figs 6, 7 and 8 respectively".
10. Page 16, line 4, if 5 MW, should become of 5 MW. Also in line 10 "voltages very fluctuate" should become "voltages fluctuate a lot".

*We have corrected the paper based on the minor comments/suggestions above.*

# CREDIT AUTHOR STATEMENT

**Ardiaty Arief:** Conceptualization, Methodology, Simulation, Validation, Writing- Original draft preparation

**Muhammad Bachtiar Nappu**: Software, Simulation, Investigation and Validation.

**Zhao Yang Dong**: Conceptualization, Methodology, Supervision, Reviewing and Editing.

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

**Date:** Sep 14, 2021
**To:** "Ardiaty Arief" ardiaty@eng.unhas.ac.id
**From:** "Chongqing Kang" epsr-thu@tsinghua.edu.cn
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Reviewer #1: Authors seem to have properly addressed the issues raised by the reviewers.

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Ms. Ref. No.: EPSR-D-21-00535
Title: Dynamic Under Voltage Load Shedding Scheme Considering Composite Load Modeling
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Dear Dr. Ardiaty Arief,
Thank you for submitting your paper entitled, "Dynamic Under Voltage Load Shedding Scheme Considering Composite Load Modeling".

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Reviewers' comments:

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The reviewer has some questions that might need to be addressed before the manuscript is considered fit for publication:
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5. Clarify the connection between Figures 9 and 10 Table III.
6. Please provide a more clear figure with the sequence of events with fewer buses and distinctive stages, i.e. disturbance, load sheding.
7. In Table IV, for the 4th iteration I see that the DVPS for bus 13 (10.65) is larger than for bus 9 (9.88). Why do you shed load from 9? There is an upper limit in the load shedding?
Minor comments
1. In page 6, 1st paragraph, last sentence please revisit, i.e. remove "hence" or rephrase.
2. Section 1, last paragraph, please change roman numerals for sections with numbers. Also replace any other

reference.
3. In subsection 2.2, second line, replace "analysis including in the UVLS design" with "analysis included in the UVLS design".
4. Paragraph 2.2.1, first sentence, "loads are content on the voltage of a bus" must become "loads depend on the voltage of a bus". Also remove the second or at the end of the sentence, it is polynomial equations.
5. Page 10, third line from the bottom, "executed" should become "calculated".
6. Page 11, first line, "notifies" should become "express".
7. Page 12, Step 1, I think you should change "Calculation" with "Set".
8. Subsection 4.2, "static load and 20% dynamic load. In exception, on bus 8" should become "static load and 20% dynamic load, with an exception, on bus 8".
9. Page 15, section 5., second paragraph, "Figs 6, 7 and 8 correspondingly" should become "Figs 6, 7 and 8 respectively".
10. Page 16, line 4, if 5 MW, should become of 5 MW. Also in line 10 "voltages very fluctuate" should become "voltages fluctuate a lot".

While submitting the revised manuscript, please double check the author names provided in the submission so that authorship related changes are made in the revision stage. If your manuscript is accepted, any authorship change will involve approval from co-authors and respective editor handling the submission and this may cause a significant delay in publishing your manuscript.

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**Ardiaty Arief -** <ardiaty@eng.unhas.ac.id> Tue, Apr 13, 2021 at 10:03 AM
To: thiar@engineer.com, muhbachtiar@gmail.com

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**Ardiaty Arief -** <ardiaty@eng.unhas.ac.id> Fri, Apr 30, 2021 at 11:33 AM
To: Joe Dong <joe.dong@unsw.edu.au>

Dear Prof. Dong,

I am happy to inform you that this manuscript was accepted with major revision and I have revised the paper according to the reviewers' suggestions and comments. I enclosed the revised version and my response to reviewers. Meanwhile, I have the turnitin check and proofread for the paper. If you are ok with the revision, I will re-submit it again.

Thank you very much for all your valuable assistance. Wish you and your family all the best. Stay safe and healthy.

Warm regards,
Ary

---------- Forwarded message ---------
From: **Chongqing Kang** <em@editorialmanager.com>
Date: Sun, Apr 11, 2021 at 11:54 AM
Subject: Your Submission
To: Ardiaty Arief <ardiaty@eng.unhas.ac.id>

[Quoted text hidden]

**2 attachments**

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# Submission Confirmation for EPSR-D-21-00535R1

2 messages

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**Chongqing Kang** <em@editorialmanager.com> Mon, May 3, 2021 at 11:47 AM
Reply-To: Chongqing Kang <epsr-thu@tsinghua.edu.cn>
To: Ardiaty Arief <ardiaty@eng.unhas.ac.id>

Ms. Ref. No.: EPSR-D-21-00535R1
Title: Dynamic Under-Voltage Load Shedding Scheme Considering Composite Load Modeling
Article Type: Research Paper

Dear Dr. Ardiaty Arief,

Your revised manuscript was received for reconsideration for publication in Electric Power Systems Research.

You may check the status of your manuscript by logging onto the Editorial Manager as an Author at https://www.editorialmanager.com/epsr/.

Your username is: ardiaty@eng.unhas.ac.id

If you need to retrieve password details, please go to:
https://www.editorialmanager.com/epsr/l.asp?i=630682&l=DXVR188E

Kind regards,

Editorial Manager
Electric Power Systems Research

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For further assistance, please visit our customer support site at http://help.elsevier.com/app/answers/list/p/7923. Here you can search for solutions on a range of topics, find answers to frequently asked questions and learn more about EM via interactive tutorials. You will also find our 24/7 support contact details should you need any further assistance from one of our customer support representatives.

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In compliance with data protection regulations, you may request that we remove your personal registration details at any time. (Use the following URL: https://www.editorialmanager.com/epsr/login.asp?a=r). Please contact the publication office if you have any questions.

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**Ardiaty Arief -** <ardiaty@eng.unhas.ac.id> Mon, Sep 13, 2021 at 11:51 AM
To: Chongqing Kang <epsr-thu@tsinghua.edu.cn>

Dear Prof. Kang,

I am just wondering about my paper. I have submitted the revision in May and I have not received any notification until now. I would appreciate it if you can inform me about it.

Thank you very much for your kind attention.

Kind regards,
Ardiaty
[Quoted text hidden]

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# Your Submission

1 message

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**Chongqing Kang** <em@editorialmanager.com> Tue, Sep 14, 2021 at 3:29 PM
Reply-To: Chongqing Kang <epsr-thu@tsinghua.edu.cn>
To: Ardiaty Arief <ardiaty@eng.unhas.ac.id>

Ms. Ref. No.: EPSR-D-21-00535R1
Title: Dynamic Under-Voltage Load Shedding Scheme Considering Composite Load Modeling
Electric Power Systems Research

Dear Dr. Ardiaty Arief,

I am pleased to confirm that your paper "Dynamic Under-Voltage Load Shedding Scheme Considering Composite Load Modeling" has been accepted for publication in Electric Power Systems Research.

Comments from the Editor and Reviewers can be found below.

Your accepted manuscript will now be transferred to our production department and work will begin on creation of the proof. If we need any additional information to create the proof, we will let you know. If not, you will be contacted again in the next few days with a request to approve the proof and to complete a number of online forms that are required for publication.

Thank you for submitting your work to this journal.

With kind regards,

Chongqing Kang
Editor
Electric Power Systems Research

Comments from the Editors and Reviewers:

Reviewer #1: Authors seem to have properly addressed the issues raised by the reviewers.

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# Your Submission

4 messages

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**Chongqing Kang** <em@editorialmanager.com> Thu, Sep 16, 2021 at 7:15 AM
Reply-To: Chongqing Kang <epsr-thu@tsinghua.edu.cn>
To: Ardiaty Arief <ardiaty@eng.unhas.ac.id>

Ms. Ref. No.: EPSR-D-21-00535R1
Title: Dynamic Under-Voltage Load Shedding Scheme Considering Composite Load Modeling
Electric Power Systems Research

Dear Dr. Ardiaty Arief,

A final disposition of "Accept" has been registered for the above-mentioned manuscript.

Kind regards,

Electric Power Systems Research

Comments from the Editors and Reviewers:

Reviewer #1: Authors seem to have properly addressed the issues raised by the reviewers.

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**Ardiaty Arief -** <ardiaty@eng.unhas.ac.id> Fri, Sep 17, 2021 at 7:05 PM
To: Chongqing Kang <epsr-thu@tsinghua.edu.cn>

Dear Prof. Chongqing Kang,

Thank you very much for your notification. I am looking forward to hearing from you again.

Best regards,
Ardiaty

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**Ardiaty Arief -** <ardiaty@eng.unhas.ac.id> Fri, Sep 17, 2021 at 7:08 PM
To: Joe Dong <joe.dong@unsw.edu.au>