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Power Generation Optimization Based on Steady State Stability Limit Using Particle Swarm Optimization (PSO)

Joko Pitono, Adi Soeprijanto, Mauridhi Hery Purnomo, Indar Chaerah Gunadin

Abstract – *The growth of electricity consumers causes increasing problems on the stability of power systems. Meanwhile, efficiency of operational method is also an important issue. The objective of this paper is to combine economic and stability analysis at once. This is done by scheduling electricity generation considering steady state stability limit. The proposed method is derived from REI-Dimo equation, and the objective function is obtained by optimization process using Particle Swarm Optimization (PSO) algorithm. The result of simulation shows that using PSO, lower operational cost and higher stability steady state limit can be achieved. It is expected that this method can be an alternative in optimal operation in power systems.*

***Keywords**: Power Optimization, Steady-State Stability Limit, REI Dimo, PSO, Objective Function*

Nomenclature

E_m	Internal voltages of the machines
δ_m	Internal angles of the machines with reference to the voltage V on the load bus
v_k^i	Particle Velocity
$c_1 c_2$	Cognitive and social parameters
p_k^i	Best remembered individual particle position
x_k^i	Particle Posisition
$r_1 r_2$	Random numbers between 0 and 1
p_k^g	Best remembered swarm position
$\delta_1 - \delta_3, \beta_1 - \beta_3$	Characteristic values of each generator
E_1, E_2, E_3	Voltages of each generator
REI	Radial Equivalent Independent
OPF	Optimal Power Flow
PSO	Particle Swarm Optimization
SCADA	Supervisory Control and Data Acquisition
EMS	Energy Management Systems

I. Introduction

Power electrical energy supply system faces its main problem with efficiency on the generator, transmission, and distribution system or combination of these three matters.

Problem solving efforts are concentrated on minimizing operational cost of fuel consumption which has become the objective function and other requirements as the constraints.

There are various OPF formulation depends on its objective functions and certain constraints being developed. The researchers have developed and concentrate on OPF problems solving by considering the system security [1], [2].

The last optimization techniques have been developed in a different area of electrical energy system are single objective function PSO, multiple objective functions PSO, and hybrid PSO.Singh and Erlich have tried to estimate of optimal block incremental cost from the instantaneous incremental heat rate curve of generating unit using PSO approach [3]. K. Thanushkodi has achieved appropriate results in applying PSO technique to solve Economic Dispatch using a smooth and non-smooth cost function by considering the effects of valve-point loading [4].

Recently, field operator (dispatcher) uses two criteria for generator loading pattern to achieve the most economical power system operation. The first criterion is according to cost per kW (merit order) rank. This means that the the cheapest generator will be operated first, then the second and so on until the most expensive generator.

Its simplicity is an advantage, but this method may have disadvantage also since it does not consider the distance between generator and load. It may be possible that generator with lowest cost per kW is not economical due to the distance between generator and supplied load (high power loss during transmission).

The second criterion in the generator loading pattern is load curve. By referring to the load curve, generator loading can be planned step by step. For similar situation, the previous record of load curve can be used as reference point since in reality, loading of a power system is repetitive. This method will ease up the operator or dispatcher during planning or commissioning of generator loading operation.

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In the present paper, generator real power rescheduling is considered as the means for enhancing steady state stability of a power system. The method proposed in this paper is built upon the PSO. From the steady state stability review, power generators with lower impedance to the power load or the closest one, will have a higher level of stability compared to those with higher impedance.

This situation occurs as a result of power transfer increasing to the power load, hence the limit level of the steady state stability increased as well. Power generators with the closest impedance to the load will be operated at the maximum level, followed by other generators.

Through this approach, the level of system stability will increase.

II. Problem Description

In power system, the solution to economic operational problem is to define each generator units to supply required load with optimum cost while still put into account the maximum power which can be generated by each generators.

System configuration consists of N generators connected to 23 bus-bar system will be used as a plant in this paper. The input for each generator (Fi) represents basic cost rate of each unit.

The output of each unit (Pi) is the power which is generated by thermal generator unit. The limit of this operational system is the amount of generated power must match the required load. Total generation cost is the sum of generation costs from each generator.

The influence of economic dispatch in steady state stability analysis be concerned in this paper.

It is described that Dimo REI equivalent method will be used to analyze the steady state stability index.

The computation of the reactive power criterion instead of evaluating the eigenvalues of the dynamic Jacobian determinant results in an increase of the computational speed by at least one order of magnitude and is at the core of the fast and relatively accurate technique developed by Paul Dimo [5], [6]. That Dimo's method has been successfully implemented and is currently used in several SCADA/EMS installations to compute the system load ability limits in real time and to continuously monitor the distance to instability [5]-[10].

When the generation pattern changes, there will be changes to the steady state stability index. With Equation (1), the stability index for each change of the generation operation can be calculated [5]:

$$\frac{d\Delta Q}{dV} = \sum_m \frac{Y_m E_m}{\cos\delta_m} - 2\left(\sum_m Y_m + Y_{load}\right)V \qquad (1)$$

where:

E_m = internal voltages of the machines (assumed to remain constant, unaffected by small adjustments made under steady-state stability conditions).

δ_m = internal angles of the machines with reference to the voltage V on the load bus (either fictitious or actual).

II.1. Test Power System

The Plant for simulation is the 500 kV Java-Bali Power System as shown in Fig. 1. The data of generator characteristics and cost, line impedances and an operating condition are shown at Table I and Table II.

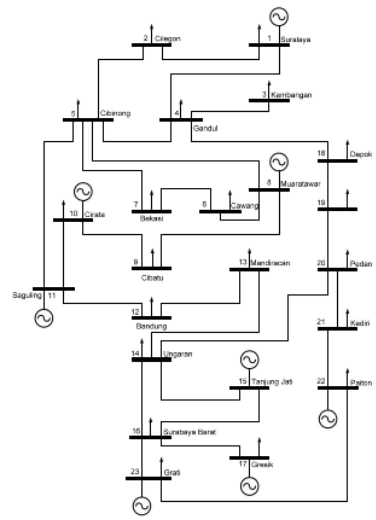

Fig. 1. Single Line Diagram of 500 kV Java-Bali Power System

TABLE I
LINE DATA OF 500 KV JAVA-BALI POWER SYSTEM

From Bus	To Bus	R (pu)	X(pu)	B (pu)
1	2	0,000626496	0,007008768	0
1	4	0,006513273	0,062576324	0,01197964
2	5	0,013133324	0,146925792	0,007061141
3	4	0,001513179	0,016928309	0
4	5	0,001246422	0,01197501	0
4	18	0,000694176	0,006669298	0
5	7	0,00444188	0,0426754	0
5	8	0,0062116	0,059678	0
5	11	0,00411138	0,04599504	0,008841946
6	7	0,001973648	0,01896184	0
6	8	0,0056256	0,054048	0
8	9	0,002822059	0,027112954	0
9	10	0,00273996	0,026324191	0
10	11	0,001474728	0,014168458	0
11	12	0,0019578	0,0219024	0
12	13	0,00699098	0,0671659	0,01285827
13	14	0,013478	0,12949	0,024789624
14	15	0,01353392	0,15140736	0,007276522
14	16	0,01579856	0,1517848	0,007264438
14	20	0,00903612	0,0868146	0
15	16	0,037539629	0,360662304	0,017261339
16	17	0,00139468	0,0133994	0
16	23	0,003986382	0,044596656	0
18	19	0,014056	0,157248	0,030228874
19	20	0,015311	0,171288	0,032927881
20	21	0,010291	0,115128	0,022131855
21	22	0,010291	0,115128	0,022131855
22	23	0,004435823	0,049624661	0,009539693

II.2. Particle Swarm Optimization

PSO algorithm is based on particles inside a population that work together to solve the existing problems regardless of its physical positions. PSO algorithm combines the local search method and global search method to balance between exploration and exploitation [4], [13], [14].

PSO has several similarities with GA. A system is started from a population formed by random solutions, and system will seek for optimization through random generation changes.

Each particle stores the position traces in the search space is defined as the best solution has been achieved. Personal best (pbest) is the best the value of the particle, while the global best (gbest) is the best value which takes into account all the particles in the population.

In iteration process, each particle is given information about the latest gbest value that occurs the mechanism to share information in one direction to make the process of finding the best solution with rapid convergence movement.

PSO algorithm consists of three steps [11], [12], namely determining the particle's position and velocity, velocity update, and position update. The position x_k^i and velocity v_k^i of particles randomly initialized using the value of the highest and lowest variable according to the design, while the rand (r) is a random value between 0 and 1.

Each particle tries to update its position using such information, current position, current velocity, distance between the current position of the pbest and the current position of gbest. Mathematically particle velocity update (v_{k+1}^i) shown in Eq. (2):

$$v_{k+1}^i = v_k^i + c_1 r_1 \left(p_k^i - x_k^i \right) + c_2 r_2 \left(p_k^g - x_k^i \right) \frac{1}{2} \quad (2)$$

Achieving the results obtained from the new velocity calculation for each particle based on the distance from pbest owned and distance from the gbest position. Particle position update (x_{k+1}^i) shown in Eq. (3):

$$x_{k+1}^i = x_k^i + v_{k+1}^i \quad (3)$$

III. Methodology

OPF problem is non-linear optimization problem with objective function and constraints are not linear. This used to calculate the generation system and distribution of electric power in order to obtain the best results and most profitable. Methods of problem solving in the conventional OPF, namely the Newton method, Gradient and Interior Point, has been used extensively.OPF problem solving required non-linear equations, the description of optimization, security and operation of power systems which in general can be written in Eq. (4) to Eq. (6):

$$\text{minimize } F(x,u) \quad (4)$$

subjected to:

$$g(x,u) = 0 \quad (5)$$

$$h(x,u) \le 0 \quad (6)$$

where:

$$x^T = \left[\delta V_L^T \right]$$

$$u^T = \left[P_G^T \; V_G^T \; t^T \; Q_{SH}^T \right]$$

Defining Objective Function

For example: A power system consists of three generators and loads center. Illustration of the system can be described in Fig. 2.

TABLE II
OPERATING CONDITION

Bus No.	Load		Generation		Injected
	MW	MVAr	MW	MVAr	MVAr
1	153	45	3332.176	988.564	0
2	703	227	0	0	0
3	760	261	0	0	0
4	544	181	0	0	0
5	697	215	0	0	0
6	760	181	0	0	0
7	646	170	0	0	0
8	0	0	1470	679.361	0
9	823	317	0	0	0
10	680	245	400	484.322	0
11	0	0	535	1043.085	0
12	590	351	0	0	0
13	397	136	0	0	0
14	329	363	0	0	0
15	0	0	830	361.87	0
16	862	317	0	0	0
17	210	91	810	608.616	0
18	0	0	0	0	0
19	277	17	0	0	0
20	524	244	0	0	-158
21	358	206	0	0	-193
22	839	272	2820	895.043	-96
23	130	193	198	395.97	0
Total	10282	4032	10395.18	5456.832	-447

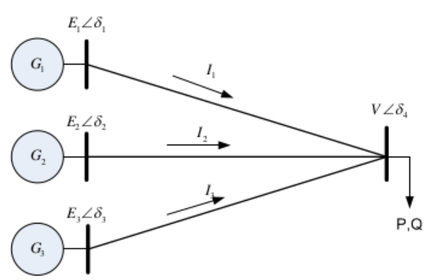

Fig. 2. System Illustrations Schema

Objective function of system shown in Fig. 2 can be described as (7) and (8):

$$\frac{dQ}{dV} = \sum_{i=0}^{m} \frac{Y_m E_m}{\cos d_m} - 2\left(\sum_{i=0}^{m} Y_m + Y_{load} \right) V \tag{7}$$

$$\frac{dF}{dP} = 2\alpha P + \beta = 0 \tag{8}$$

$$\frac{dQ}{dV} = \text{minimize}$$

$$\frac{dF}{dP} = \text{minimize}$$

$$d = \frac{I_1}{\cos(\delta_1 - \delta_4)} + \frac{I_2}{\cos(\delta_2 - \delta_4)} + \frac{I_3}{\cos(\delta_3 - \delta_4)}$$

where:
d is the total comparison of current each line with cosines of sending and receiving angle.

Eq. (7) is derived from REI Dimo [6] and Eq. (8) is derived from Lagrange [2]. To get the cheapest operation cost and the highest index of stability limit, Eq. (7) and (8) should be optimized parallel.

The procedure of optimization process each generator can be described as follow:

For generator 1:

$$\begin{aligned} &\frac{dF}{dP} = 2\alpha_1 P_1 + \beta_1 = 0 \\ &2\alpha_1 P_1 + \beta_1 = 0 \\ &P_1 = -\frac{\beta_1}{2\alpha_1} \end{aligned} \tag{9}$$

Eq. (7) can be substituted into:

$$\begin{aligned} &E_1 I_1 \cos\theta_1 = -\frac{\beta_1}{2\delta_1} \\ &I_1 = -\frac{\beta_1}{2\delta_1 E_1 \cos\theta_1} \end{aligned} \tag{10}$$

Substituting Eq. (8) into Eq. (6) results in:

$$\begin{aligned} d = &\frac{-\beta_1}{2\delta_1 E_1 \cos(\delta_1 - \delta_4)} + \frac{-\beta_2}{2\delta_2 E_2 \cos(\delta_2 - \delta_4)} + \\ &+ \frac{-\beta_3}{2\delta_3 E_3 \cos(\delta_3 - \delta_4)} \end{aligned} \tag{11}$$

where:
$\delta_1, \delta_2, \delta_3, \beta_1, \beta_2, \beta_3$ are characteristic values of each generator.
E_1, E_2, E_3 are voltages of each generator (obtained from load flow).

Another way:

$$P_1 = \frac{E_1 V}{X_1} \sin(\delta_1)$$

$$I_1 = \frac{P_1}{V \sin(\delta_1)}$$

$$\begin{aligned} d = &\frac{P_1}{V \sin(\delta_1)\cos(\delta_1 - \delta_4)} + \frac{P_2}{V \sin(\delta_2)\cos(\delta_2 - \delta_4)} + \\ &+ \frac{P_3}{V \sin(\delta_3)\cos(\delta_3 - \delta_4)} \end{aligned}$$

Then, obtained:

Then, obtained:

$$d = \frac{1}{V}\left\{ \begin{aligned} &\frac{P_1}{\sin(\delta_1)\cos(\delta_1 - \delta_4)} + \frac{P_2}{\sin(\delta_2)\cos(\delta_2 - \delta_4)} \\ &+ \frac{P_3}{\sin(\delta_3)\cos(\delta_3 - \delta_4)} \end{aligned} \right\}$$

where:
P_1, P_2, P_3 are powers of each generator which will be optimized.
$\delta_1, \delta_2, \delta_3, \delta_4$ are load angle from bus (obtained from load flow)
V is Load Bus Center Voltage (obtained from load flow)

The smaller the value d, the more stable the system will be (Minimize Optimization)

By using optimization process the most optimum operation with good steady state stability index can be achieved:

$$e = 2\left(\sum_{i=0}^{m} Y_m + Y_{load} \right) V \tag{12}$$

where:

$$Y_{load} = \frac{Q_{load}}{V^2}$$

Those equations can be substituted into:

$$e = 2\left(Y_1 + Y_2 + Y_2 + \frac{Q_{load}}{V^2} \right) V$$

$$e = 2\left(\frac{P_1}{E_1} + \frac{P_2}{E_2} + \frac{P_3}{E_3} + \frac{Q_{load}}{V^2} \right) V$$

$$e = -\left(\frac{\beta_1}{\alpha_1 E_1} + \frac{\beta_2}{\alpha_2 E_2} + \frac{\beta_3}{\alpha_3 E_3} + \frac{Q_{load}}{2V^2} \right) V$$

IV. Result and Discussion

To verify performance of proposed method, several peak load operating conditions were used as test systems. Fig. 3 shows that the value of SSSL obtained by PSO is better than that by base case optimization.

From Tables III and IV, it can be shown that using PSO algorithm the steady state stability limit can be improved. With active power of 10282 MW and reactive power of 3021 MVAR, without using PSO will result in steady state stability index of -46.872. While using PSO, steady state stability index of -49.143 can be achieved.

This shows that using PSO can increase the steady state stability limit of a system. Also when the active load is increased to 10582 MW and reactive load is also increased to 4148.144 MVAR, without using PSO will result in steady state stability index of -45.4142 compared to -48.3255 when PSO is used.

From economic point of view, it can be concluded that on the same required load, total generation using PSO is 11248 MW compared to 12230 MW without using PSO. Tables V and VI shown the total generation in Java-Bali 500 kV for base case and after optimation using PSO.

The convergence of used PSO algorithm can be seen in the Fig. 3.

TABLE III
STEADY STATE STABILITY VALUES WITHOUT PSO

P LOAD (MW)	Q LOAD (MVAr)	D	E	Index
10282	4032	62.267	109.0542	-46.7872
10582	4148.144	62.9021	108.3163	-45.4142

TABLE IV
STEADY STATE STABILITY VALUES WITH PSO

P LOAD (MW)	Q LOAD (MVAr)	D	E	Index
10282	4032	60.4741	109.6171	-49.143
10582	4148.144	61.2499	109.5754	-48.3255

TABLE V
TOTAL GENERATION WITHOUT PSO

Without PSO		Voltage	Angle
Real Power of Gen 1 =	5170.698	1.02	0
Real Power of Gen 2 =	1470	1	-12.443
Real Power of Gen 3 =	400	1	-14.601
Real Power of Gen 4 =	535	1	-14.676
Real Power of Gen 5 =	830	1	-27.884
Real Power of Gen 6 =	810	1	-36.999
Real Power of Gen 7 =	2820	1	-47.016
Real Power of Gen 8 =	198	1	-41.905
Total Generation =	12.230		

TABLE VI
TOTAL GENERATION WITH PSO

USING PSO		Voltage	Angle
Real Power of Gen 1 =	780.482	1.02	0
Real Power of Gen 2 =	1259.33	1	1.309
Real Power of Gen 3 =	820.339	1	0.69
Real Power of Gen 4 =	480.13	1	0.336
Real Power of Gen 5 =	815.712	1	3.547
Real Power of Gen 6 =	2031.082	1	1.314
Real Power of Gen 7 =	3455.381	1	-13.354
Real Power of Gen 8 =	1606.132	1	-4.372
Total Generation =	11.248		

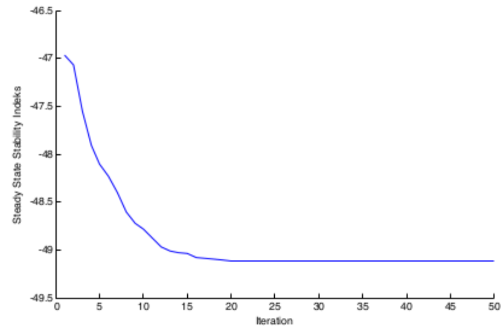

Fig. 3. Graph of PSO Convergency

Limit the maximum loading is influenced by the value of impedance between the load and generator. If the impedance value is smaller, the maximum power transfer will increase. This relationship can be seen in the following equation:

$$P = \frac{E_s E_R}{X_T} sin(\delta_s - \delta_R) \quad (13)$$

Using PSO method, operations of generator is adjusted by impedance value among the generators. Generator which has the smallest impedance value, would be prioritized for maximum operating, then followed by other generators with a larger impedance values. *P* value will increase with the increasing level of voltage and decreasing value of X_T.

Fig. 4. shows the relationship of *P* to changes in the value of *d* and *e* . The best SSSL of a system can be obtained by decreasing value of *d* and increasing value of *e*. PSO method has the lowest value of *d* and *e* of the largest value so that the steady state stability limit for this method to be greatest.

Fig.5. shows that the PSO method resulting more gentle slope than base case optimization. It's mean that PSO method can improved the steady state stability limit.

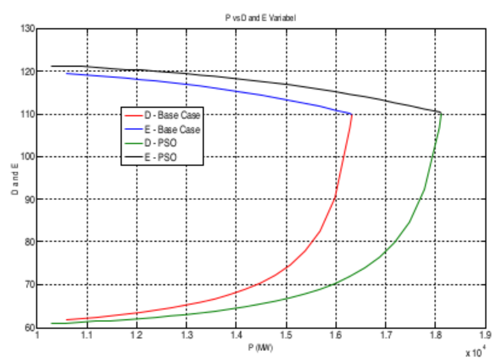

Fig. 4. P vs D and E Variables

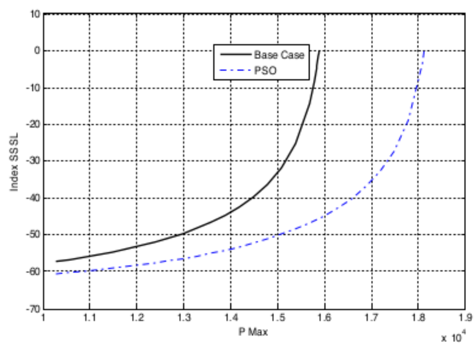

Fig. 5. P vs SSSL indeks

V. Conclusion

The simulation results show that the power generation optimization method proposed in this paper, is able to improve steady state stability index when compared base case operation. This can be seen from the increasing of steady state stability limit. PSO method is expected to be implemented at the peak load operation or at special events require a better level of security.

With already in implementations Dimo REI method on real-time monitoring systems in several countries, it is expected that the method proposed in this paper becomes an additional tool to facilitate the optimal and secure operation in power systems.

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