Security and Stability Improvement of Power System due to Interconnection of DG to the Grid

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Abstract. This paper developed a novel method to improve the performance of power network based on system stability viz.: voltage stability index and line stability factor, as well as system security i.e. a bus voltage vocation factor and thermal limits of the transmission line. This method has been analyzed and evaluated in a standard test system due to interconnection of a distributed generation (DG) into a grid in anticipation of an increase in load demand. To ensure the stability and security of the system as a result of the interconnection of the DG, it has been done by optimal placement of one type of shunt Flexible AC Transmission Systems (FACTS) controller, namely Static Var Compensator (SVC). The device which is proficient for injecting and absorbing reactive power is modeled and subsequently combined in Newton Raphson power flow analysis. The effectiveness of the methodology developed has been successfully tested on IEEE 14-bus standard test system with integration of the DG into the test system.

Keywords: DG, FACTS, SVC, system stability, system security

1. Introduction

In recent decades, the electric power system faces new challenges as a result of the impact of deregulation and restructuring of the electricity market [1]. Along with the deregulation of the electrical load continues to increase so that the need for the addition of new power plants into the electric power system network (grid) in anticipation of an increase in load demand of consumers. This resulted in transmission lines to distribute power loads approaching its thermal limits.

This condition would attract electric power system to find the right way that enables the distribution of electric power by consumers to be more efficient in a way to control the flow of electrical power [2]. A lot of the latest technology developed in the electric power system, which makes the utility is able to control the flow of power in anticipation of an increase in electric power loadability, thermal limit of the line, the stability of the transmission system, and improve the security of the transmission system [3]. In addition, a variety of modern control devices have been developed and used to maximize the power transfer capability while minimizing power loss transmission system, which leads to efficient utilization and improve performance of existing power systems [4].

When compared with the control strategy corrective, such as scheduling and termination load generation, utilization of modern control systems such as FACTS devices in the future is a more economical alternative in efforts to reduce operating costs and investment in the development of new network system, although the cost of the device still relatively expensive and quite complicated operation [5], [6].

To anticipate the demand for electricity continues to increase, and gradually reduce dependence on electricity supplies from outside the island, the operation of a distributed generation (DG) are absolutely necessary. Operation of this plant can provide influence on grid's system performance which is represented in the reduction of the voltage profile and power losses of the grid system. In order for the operation of the plant is able to anticipate the increase in electrical load that occurs for several years into the future with continuity and reliability it needs to be analyzed and evaluated the stability and security of the grid system.

This research proposes a novel method based on evolutionary optimization techniques known as Particle Swarm Optimization (PSO) in analyzing and evaluating the stability and security of the power system at a maximum system loadability by the operation of a distributed generation (DG). This is done by optimal placement of a shunt FACTS controller i.e. SVC on a IEEE 14-bus standard test system [7]. With interconnecting DG into the grid, it still ensures the stability of the system at its margins, namely: fast voltage stability index (FVSI) and line stability factor (LQP) and maintain the security of the system viz.: bus violation factor and thermal limit. In addition, to avoid an excessive increase in line losses due to increased system loadability, the technique is also being developed simultaneously to minimize active power losses as a result of DG interconnection to the grid with the aim to improve the performance of the system.

2. Problem Formulation

2.1. DG Modeling

A precise dynamic modeling of DG unit, to study the dynamic behavior, is a key issue to obtain an adequate idea of the impact on the network resulting from the presence of the generating units follows a few distractions. Synchronous machines must be modeled through conventional state equation that describes the electrical machine, automatic voltage regulator, equations swing, speed regulator and the main engine [8]. However, this modeling depends on the type of plant. In some industrial plants which have cogeneration facilities speed regulator became active only in an isolated mode of operation. Generator with the power electronic converter can be modeled as a controlled current source or sources of active and reactive power [9] since the fast transients in this converter, associated with the operation of electronic switches and controls, which are not interesting in the analysis.

2.2. Shunt FACTS Modeling

Static Var Compensator (SVC) is one type of shunt FACTS controllers which are widely used in modern electrical systems in some parts of the world. The SVC is connected in parallel (shunt) with the load bus to compensate of the inductive reactance on the bus. In this study SVC is modeled as an ideal reactive power injection at bus i [10].

$$\Delta Q_i = Q_{SVC} \tag{1}$$

The model is completed by the algebraic equation expressing the reactive power injected at the SVC node [11], [12]:

$$Q_{svc} = b_{SVC} V^2 \tag{2}$$

where, V and b_{SVC} are the voltage magnitude of bus at which the component are connected and total reactance of the controller, respectively

2.3. System Loadability

To ensure the security of the system due to DG interconnection to the grid, it done by increasing the system loadability without exceeding their thermal and bus violation limit factor.

$$\text{Maximize} \quad F_1(\mathbf{x},\mathbf{u}) = \{\lambda_1\} \tag{3}$$

$$\text{Subject to } VL = \sum_{i=1}^{N_l} OLL_i \times \sum_{j=1}^{N_b} BVV_j \tag{4}$$

where VL is the thermal and bus violation limit factor, OLL_i and BVV_j represent the overloaded line factor and branch the bus voltage violation factor, respectively; N_l and N_b are the total numbers of transmission lines and buses, respectively. In addition λ_l is a load parameter of the system, which intends to locate the maximum sum of power that the network is able to supply within the system security margin [4].

2.4. Total Power Losses

An exact loss equation in (5) bellow represented the total real power loss in a power system [13].

$$P_{loss}(\mathbf{x},\mathbf{u}) = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j + P_iQ_j\right)\right] \tag{5}$$

where

$$\alpha_{ij} = \frac{r_{ij}}{V_i V_j}\cos(\delta_i - \delta_j) \quad ; \quad \beta_{ij} == \frac{r_{ij}}{V_i V_j}\sin(\delta_i - \delta_j)$$

$V_i\angle\delta_i$ complex voltage at the bus i^{th};
$r_{ij} + jx_{ij} = Z_{ij}$ ij^{th} element of [$Zbus$] impedance matrix;
P_i and P_j active power injections at the i^{th} and j^{th} buses, respectively;
Q_i and Q_j reactive power injections at the i^{th} and j^{th} buses, respectively;
N number of buses.

2.5 *Stability Constraints*

a. Fast voltage stability index

Fast Voltage Stability Index (*FVSI*) proposed by Musirin [14] is utilized in this paper to assure the safe bus loading. The *FVSI* is the device used to indicate the voltage stability condition formulated based on a line or a bus as defined by

$$FVSI_{ij} = \frac{4Z^2 Q_j}{V_i^2 X} \tag{9}$$

where, Z is the line impedance, X is the line reactance, Q_j is the reactive power at the receiving end, and V_i is the sending and voltage. *FVSI* index incorporation in the controller assures that no bus will collapse due to overloading.

b. Line stability factor

System stability index is also assured by Line Stability Factor (*LQP*) proposed by A Mohamed *et al* [15]. The formulation begins with the power equation in a power system and is expressed as

$$LQP = 4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2}P_i^2 + Q_j\right) \tag{10}$$

where, X is the line reactance, V_i is the sending end voltage, P_i is the sending end real power, and Q_j is the receiving end reactive power. The *LQP* must be kept less than 1.00 to maintain a stable system. *LQP* assure the controller that no line is over loaded under any grid condition.

3. Methodology Development

3.1 *Overview of PSO*

In a PSO system [16], each particle in search space is defined by the following elements: x_i^k is the value of particle i at generation k. The update of particle i in the search space is defined by (11); p_{best} is the best value found by the particle i until generation k, v_i^{k+1} is the velocity of particle i at generation k. The update of velocity during the search procedure is presented by (12); g_{best} is the best particle found in the group until generation k.

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{11}$$

$$v_i^{k+1} = w \times v_i^k + c_1 \times rand_1 \times \left(p_{best_i} - x_i^k\right) + c_2 \times rand_2 \times \left(g_{best} - x_i^k\right) \tag{12}$$

where, ω is weighting function, c_j isweighting factor, $rand_i$ is random number between 0 and 1, p_{best} and p_{best} of particle i and g_{best} of the group repectively.
The following weighting function is usually utilized [17]:

$$\omega = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{iter_{max}} \times iter \tag{13}$$

where: ω_{max}, ω_{min}, $iter_{max}$ are the initial weight, final weight, and the maximum iteration number, respectively.

3.2 *Calculation of Fitness Function*

The optimization problem for the best promising placement of the SVC controller is changed into an unconstrained optimization problem using a penalty factor (*PF*) as given in (14). This becomes the fitness function (*FF*) in the PSO technique.

$$\mathrm{FF} = \mu_1 F_1 - \mu_2 F_2 + PF \times |VL - 1| \qquad (14)$$

Equation (14) is composed of three parts equation. The first rate is a function of the goal to maximize the loading system as shown equation (3), the second term is a second objective function to minimize power loss transmission line as shown in equation (5). While the last term, a constraint violation of system security according to the equation (4) which is multiplied by the PF to calculate the fitness function given by (14) for each particle. μ_i is the weighting coefficient used to adjust the tilt PSO. For each particle, the data bus line and updated according to the increase in system load. NR power flow method run to get on any bus voltage and line power flow. With this result, the value VL for each particle obtained by using (4) and the fitness function of each particle is calculated by using (14). Particles that provide maximum value to the fitness function in a population regarded as g_{best} particles. Speed and new position of each particle is calculated respectively using equations (12) and (13). This procedure is repeated until the maximum number of iterations is reached so that the value of VL and all obstacles stability as shown in (9) and (10) for particles g_{best} examined. If the value is equal to 1, then by using a particle g_{best}, the current value of the loading system can be met without a breach in the flow line power, bus voltage limit constraints and all the constraints of stability within the allowable limits. The g_{best} particles are stored together with the loading system and lines power losses. Then loading the system increases again when PSO algorithm is executed. If the value VL for g_{best} particles is not equal to 1 then the particle g_{best} cannot meet the current system loading and particle g_{best} with VL = 1 obtained in the previous step is considered as the best optimal setting. Imposition of a particle system in accordance with g_{best} regarded as maximum system loading.

4. Result and Discussion

To investigate and validate the method in solving the optimization problems developed in this study, the simulation have been implemented on IEEE 14-bus standard test system [7] using the PSO technique. The simulation has also been carried out with resolve the two objective functions simultaneously i.e. maximizing the system loadability (Max SL) whereas minimizing the active power losses (Min P_{loss}) of transmission line by considering the security and stability margins. This is done on the three cases: base case, without DG interconnection to the grid, and by optimal placement of SVC device in both cases viz.: to the base case (Case-1) and after a specified amount DG of 10 MVA, 13.8 Volt is interconnected to the grid (Case-2). The SVC device used in this study, modeled using power system analysis toolbox (PSAT) [7]. PSO parameters are presented in Table 1.

Tabel 1. PSO Parameters

c_1, c_2	ω_{max}	ω_{min}	Iteration Number	Population Number
2.0	0.9	0.4	50	50

The load is modeled as a constant PQ load with constant power and load factor increased by using the PSO technique according to the equation (10) and (11). Each additional system load that occurs in this study is assumed to be borne by the slack generator.

Table 1. Optimal Location of the SVC for bi-objective optimization

Cases	Location (bus)	*Setting (pu.)*	Max *SL (%)*	Min P_{loss} *(pu.)*
Base case	-	-	100	0.761
Case-1	14	0.98	166.46	0.474
Case-2	4	0.97	183.47	0.482

The location and setting of SVC set as a decision variable, while all bus load of test systems IEEE 14-bus chosen as candidate locations for the placement of the SVC. Based on these data [7], [18] the IEEE 14-bus fed by two generators on the bus 1 and 2, three synchronous condenser are located on bus 3, 6 and 8, with 20 line and 11 bus loads. From the simulation results carried out in both cases, found that the optimal placement and setting of SVC equipment on the IEEE 14-bus network to get Max SL and Min P_{loss} of the transmission line are presented in Table 2.

From Table 2 it can be observed that in Case-1, the SVC installation on 14-bus with a maximum setting of 0.98 pu resulted a maximal system loadability (Max SL) and the minimum active power losses line (Min P_{loss}) are 166.46% and 0.474 pu. respectively. Moreover in Case-2, after the DG interconnection to the grid on one bus load that is chosen is the bus 14, the optimal placement and setting the SVC on the bus 4 have been able to increase of the loading system up to 183.47%. The increase in load is spread proportionally almost in all of the load bus. In this condition, despite an increase in SL, P_{loss} is not much different from the Case-1 is 0.482 pu.

This result suggests that the optimal placement and setting SVC to the grid which is interconnected to the DG is not only improve the loading system (SL) but also at the same time it able to minimizing P_{loss} of the transmission line with all the security and stability system constraints are guaranteed at the limit of the allowable margin.

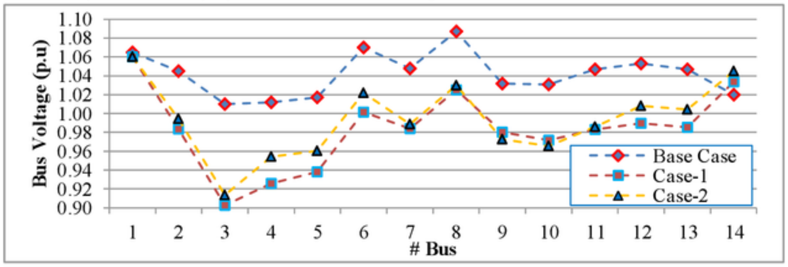

Figure 2. Voltage Profile for Case-1 and Case-2 on IEEE 14-bus standard test system

Figure 2 shows the voltage profile of the Case-2 which proves that the optimal placement of SVC at bus 4 ensure the security of the system which is at their limit allowable voltage. While Figure 3 shows the stability of the system which is represented by FVSI and LQP factor are less than one.

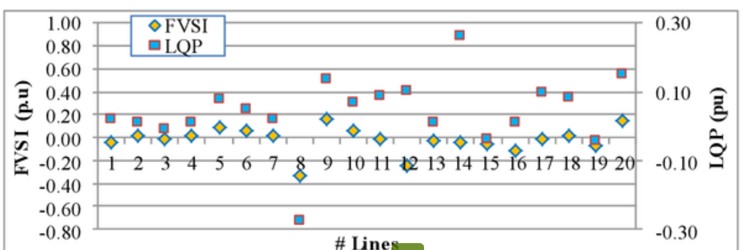

Figure 3. FVSI dan LQP for Case-2 on IEEE 14-bus standard test system

The results obtained in the IEEE 14-bus system compared to those reported in [4] as shown in Table 3. In Case-1, Max SL obtained in this study compares favorably with results reported in [4], although with the number of controllers required is the same but different types of devices. In this study, Min P_{loss} are considered, but the reference concerned with the cost of the controller because the cost of UPFC is more expensive than the cost of SVC. In addition, stability constraints applied in both studies is different. Case-2 of the standard IEEE 14-bus test system has not been reported in the reference..

Table 3: Maximum System Loadability (Max SL), Minimum P_{loss} (Min P_{loss}), and Minimum cost of FACTS (Min Cost) needed in IEEE 14-bus system

Cases	Type of FACTS	Result obtained in this study				Type of FACTS	Result reported in [4].			
		Max *SL*	Min P_{loss}	Min Cost ($\times 10^6$US$)	Stability constraint		Max *SL*	Min P_{loss}	Min Cost ($\times 10^6$US$)	Stability constraint
Case-1	SVC	166.46	0.474	-	FVSI & LQP	UPFC	150.29	-	0.2878	small signal
Case-2		183.47	0.482	-			-	-	-	

5. Conclusion

This study has successfully implemented one type of the advanced evolutionary optimization techniques, namely PSO which is used to solve a bi-objective optimization problem, viz.: increasing the system loadability due to DG interconnection to the grid whereas reducing active power losses of transmission line. For agreeing the optimization problems involving simultaneous bi-objective was conducted with optimal placement of one type of shunt FACTS device namely SVC at the best location whereas ensuring the security and stability of the system which is expressed as FVSI and LQP. From the simulation results performed on the IEEE 14-bus standard test system show that system loadability can be increased to efficiently up to 83.4% of the base case using the PSO technique with an index of performance in achieving accurate and fast convergence.

In addition, the algorithm developed in this study is not only able to solve the bi-objective optimization problem, but also has superior features that include high-quality solutions, stable convergence characteristics and good calculation efficiency. Thus the proposed optimization technique can be developed further to more than two objectives and applied on a practical power system for validation and support the superiority of the proposed technique.

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