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Improving the Transient Stability-Constrained Optimal Power Flow with FACTS

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***Abstract*— The transient stability constrained optimal power flow (TSC-OPF) is a big challenge in the field of power systems. Due to the deregulation of electricity markets, power systems tend to operate closer to stability limits. Optimal power flow (OPF) is a powerful tool to weaken the conflict between economy and security, but the main obstacle faced is that, the complexity involved for OPF with transient stability constraints is several orders of magnitude higher than that of conventional OPF with merely static constraints. Therefore, consideration of Transient Stability Constraints in Optimal Power Flow (OPF) problems is becoming more and more imperative. FACTS can be very effective to power system security in case of a fault. In this paper, we concentrate on the improving transient stability-constrained optimal power flow to against single fault via the use of FACTS. Study results on IEEE 30-bus system have proved the effectiveness of using FACTS to improve transient stability-constrained optimal power flow (TSCOPF).**

***Keywords*— Transient stability; FACTS; OPF; TSC-OPF; power system**

I. Introduction

Modern power systems have grown in size and complexity because of increasing electricity demand and larger power transmissions over longer distances. Nevertheless, it is essential that security and reliability be ensured in power system operation. The main condition for reliable operation of such systems is to maintain synchronous generators running in parallel with sufficient capacity to meet the load demand at any time. A secured power system is able to withstand large disturbances without interruption of customer service. Accordingly, for proper planning and operation, after a disturbance occurs, the system survives the ensuing transient and moves into an acceptable equilibrium point where all components are operating within established limits [1]. Several methods have been investigated to determine the instability caused by a severe disturbance or a series of disturbances. These methods fall into two main categories. Conventionally, time domain (TD) simulation is used to solve the set of non-linear equations describing the system variables. TD simulation is an accurate method, but it eventually suffers from extensive computation effort for complex and large power systems. Direct methods are an alternative to TD simulation. Although transient energy based methods [2], such as extended equal area criterion method (EEAC) [3] provide techniques to assess the transient stability without solving the complex differential–algebraic equations set, transient energy based methods require many computations to determine the transient stability index and are difficult to implement in practice [4].

Modern heuristic optimisation methods, such as evolutionary algorithms (EAs) have been applied to TSC-OPF. Cai et al. [5] used the differential evolution algorithm for TSC-OPF. Yan et al. [6] combined a classical deterministic programming technique and an EA for solving the problem of TSC-OPF. EA-based methods have strong global searching capability, however, their computation burden can be very high.

Transmission networks of modern power systems have been causing problems because of growing demand and restrictions on building new lines. One of the consequences of such a system is the threat of losing stability following a disturbance. In order to expand or enhance the power transfer capability of existing transmission network the concepts of FACTS (Flexible AC transmission system) is developed by the Electric Power Research Institute (EPRI) in the late 1980s. The main objective of FACTS devices is to replace the existing slow acting mechanical controls required to react to the changing system conditions by rather fast acting electronic controls. FACTS means alternating current transmissions systems incorporating power electronic based and other static controllers to enhance controllability and increase power transfer capability [7]. FACTS devices are found to be every effective in a transmission network for better utilization of its existing facilities without sacrificing the desired stability margin. There are various forms of FACTS devices, some of which are connected in series with a line and the others are connected in shunt or a combination of series and shunt [7].

Better utilization of existing power system capacities by installing FACTS devices has become imperative. The application of FACTS in the electric power system, such as static VAr compensator (SVC), static compensator (STATCOM), thyristor-controlled series capacitor (TCSC), solid-state series controller (SSSC), thyristor switched series Capacitor (TSSC), thyristor controlled series reactor (TCSR), thyristor-switched series reactor (TSSR), thyristor controlled phase angle regulators (TCPAR), unified power flow controllers (UPFC) among others, is intended for the control of

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power flow, improvement of stability, voltage profile management, power factor correction, loss minimization, and reduced cost of production. The OPF becomes even more complex when FACTS devices are taken into consideration as control variables [7], [8].

II. Modelling of Static Compensator : STATCOM

The STATCOM is a member of the FACTS family that is connected in shunt with AC power systems [9]. The STATCOM has played an important role in the power industry since the 1980s. The STATCOM consists of one VSC and its associated shunt-connected transformer. It is the static counterpart of the rotating synchronous condenser but it generates or absorbs reactive power at a faster rate because no moving parts are involved. In principle, it performs the same voltage regulation function as the SVC (static Var compensator) but in a more robust manner because, unlike the SVC, its operation is not impaired by the presence of low voltages [10].

A schematic representation of the STATCOM and its equivalent circuit are shown in Fig. 1a and Fig. 1b, respectively.

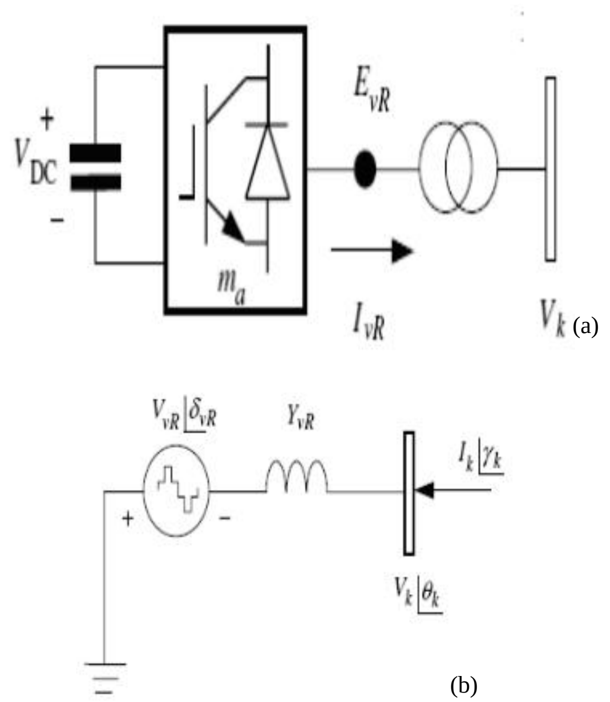

Fig. 1 Static compensator (STATCOM) system; (a) schematic representation; (b) equivalent circuit

The STATCOM will be represented by a synchronous voltage source with maximum and minimum voltage magnitude limits. The synchronous voltage source represents the fundamental Fourier series component of the switched voltage waveform at the AC converter terminal of the STATCOM [10].

The bus at which the STATCOM is connected is represented as a PVS bus, which may change to a PQ bus in the event of limits being violated. In such a case, the generated or absorbed reactive power would correspond to the violated limits. Unlike the SVC, the STATCOM is represented as a voltage source for the full range of operation, enabling a more robust voltage support mechanism. The STATCOM equivalent circuit shown in Fig. 1b is used to derive the mathematical model of the controller for inclusion in power flow algorithms.

The STATCOM is a DC/AC voltage source converter with an energy storage unit, usually a DC capacitor. Power electronic switches are used to derive an approximately sinusoidal output voltage from a DC source [9]. The exchange of active and reactive power between the STATCOM and the AC power systems can be controlled by adjusting the phase and amplitude of the converter output voltage. STATCOM can be operated in the capacitive mode (inject reactive power) by controlling the amplitude of the converter voltage to be greater AC power systems. In contrast, the magnitude of the converter voltage is controlled to be less than that of the AC power systems in order to absorb reactive power or operate the STATCOM in the inductive mode. The converter operation is associated with internal losses caused by non-ideal power semiconductor devices and passive components. Without any proper control, the capacitor voltage will be discharged to compensate for these losses. The capacitor voltage is regulated by introducing a small phase shift between the converter voltage and the AC power systems [9].

The power flow equations for the STATCOM are derived below from first principles and assuming the following voltage source representation [10]:

$$E_{vR} = V_{vR}\left(\cos\delta_{vR} + j\sin\delta_{vR}\right) \quad (1)$$

Based on the shunt connection shown in Fig. 1b, the following may be written:

$$S_{vR} = V_{vR} I^*_{vR} = V_{vR} Y^*_{vR}\left(V^*_{vR} - V^*_{k}\right) \quad (2)$$

After performing some complex operations, the following active and reactive power equations are obtained for the converter and bus k, respectively:

$$P_{vR} = V_{vR}^2 G_{vR} + V_{vR}V_k\left[G_{vR}\cos(\delta_{vR}-\theta_k) + B_{vR}\sin(\delta_{vR}-\theta_k)\right] \quad (3)$$

$$Q_{vR} = -V_{vR}^2 B_{vR} + V_{vR}V_k\left[G_{vR}\sin(\delta_{vR}-\theta_k) - B_{vR}\cos(\delta_{vR}-\theta_k)\right] \quad (4)$$

$$P_k = V_k^2 G_{vR} + V_k V_{vR}\left[G_{vR}\cos(\theta_k-\delta_{vR}) + B_{vR}\sin(\theta_k-\delta_{vR})\right] \quad (5)$$

$$Q_k = -V_k^2 B_{vR} + V_k V_{vR}\left[G_{vR}\sin(\theta_k-\delta_{vR}) - B_{vR}\cos(\theta_k-\delta_{vR})\right] \quad (6)$$

Using these power equations, the linearised STATCOM model is given by equation (7), where the voltage magnitude V_{vR} and phase angle δ_{vR} are taken to be the state variables:

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$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \\ \Delta P_{vR} \\ \Delta Q_{vR} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial \delta_{vR}} & \frac{\partial P_k}{\partial V_{vR}} V_{vR} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial \delta_{vR}} & \frac{\partial Q_k}{\partial V_{vR}} V_{vR} \\ \frac{\partial P_{vR}}{\partial \theta_k} & \frac{\partial P_{vR}}{\partial V_k} V_k & \frac{\partial P_{vR}}{\partial \delta_{vR}} & \frac{\partial P_{vR}}{\partial V_{vR}} V_{vR} \\ \frac{\partial Q_{vR}}{\partial \theta_k} & \frac{\partial Q_{vR}}{\partial V_k} V_k & \frac{\partial Q_{vR}}{\partial \delta_{vR}} & \frac{\partial Q_{vR}}{\partial V_{vR}} V_{vR} \end{bmatrix} \begin{bmatrix} \Delta \theta_k \\ \frac{\Delta V_k}{V_k} \\ \Delta \delta_{vR} \\ \frac{\Delta V_{vR}}{V_{vR}} \end{bmatrix} \quad (7)$$

III. TSC-OPF PROBLEM FORMULATION

The OPF problem consists of obtaining the optimal settings for control variables in an electric power system so that certain operational goals can be achieved. These are represented by a predefined objective function *f*, subject to a set of constraints. The operating state of a power system provided by an OPF is one that guarantees affordability, reliability, security, and dependability. Generally, the OPF problem can be expressed as [11]-[8], [12]-[13]:

$$Min\ f\,(x,\,u) \quad (8)$$

Subject to

$$h\ (x,\ u) = 0 \quad (9)$$

$$g\,(x,\,u) \le 0 \quad (10)$$

Where x is the vector of state variables, u is a vector of control variables, $f\,(x,u)$ is the objective function to be optimised, $h(x,u)$ represents the power flow equations, and $g(x,u)$ consists of state variable limits and functional operating constraints.

In general, the aim is to optimise an objective function with the solution satisfying a number of equality and inequality constraints. Any solution point that satisfies all the constraints is said to be a feasible solution. A local minimum is a feasible solution point where the objective function is minimised within a neighbourhood. The global minimum is a local minimum with the lowest value in the complete feasible region.

In this paper, the objective functions of OPF are minimization of fuel cost for all generators f_1 and active power losses minimization f_2 which can be formulated as:

$$f_1 = \min \sum_{i=1}^{ng} a_k P_{gk}^2 + b_k P_{gk} + c_k \quad (11)$$

$$f_2 = \min \sum_{k=1}^{nl} \sum_{j=1}^{nl} (P_{kj} + P_{jk}) \quad (12)$$

Where P_{gk}, n_g and n_l are the active power output generated by the i-th generator, the total number of generators and total number of branches. a_k, b_k and c_k are the cost coefficients of unit k.

A. EQUALITY CONSTRAINTS

The equality constraints $h(x,u)$ are the sets of nonlinear power flow equations that govern the power system, i.e.:

$$P_k(V,\theta) + P_{dk} - P_{gk} = 0 \quad (13)$$

$$Q_k(V,\theta) + Q_{dk} - Q_{gk} = 0 \quad (14)$$

Where P_k, Q_k, P_{dk}, Q_{dk} are the active and reactive power injections at bus k, the active and reactive power loads at bus k, respectively. P_{gk} and Q_{gk} are the scheduled active and reactive power generations at bus k, respectively. V and θ are the nodal voltage magnitudes and angles.

B. INEQUALITY CONSTRAINTS

The inequality constraints $g(x,u)$ are the set of constraints that represent the system operational and security limits like the bounds on the following:

- ✓ Generators active and reactive power outputs:

$$P_{gk}^{\min} \le P_{gk} \le P_{gk}^{\max} \quad \text{where} \quad k = 1,....., n_g \quad (15)$$

$$Q_{gk}^{\min} \le Q_{gk} \le Q_{gk}^{\max} \quad \text{where} \quad k = 1,....., n_g \quad (16)$$

- ✓ Voltage magnitudes and angles at each bus:

$$V_k^{\min} \le V_k \le V_k^{\max} \quad \text{where} \quad k = 1,....., n_b \quad (17)$$

$$\theta_k^{\min} \le \theta_k \le \theta_k^{\max} \quad \text{where} \quad k = 1,....., n_b \quad (18)$$

- ✓ Transformer tap settings:

$$T_k^{\min} \le T_k \le T_k^{\max} \quad \text{where} \quad k = 1,....., n_T \quad (19)$$

- ✓ Reactive power injections due to STATCOM:

$$Q_{STAT-k}^{\min} \le Q_{STAT-k} \le Q_{STAT-k}^{\max} \quad \text{where} \quad k = 1,....., n_{STAT} \quad (20)$$

Where T, n_T, n_b, n_{STAT} and Q_{STAT} are the transformer tap settings, total number of transformers, total number of buses, total number of STATCOM and reactive power injected by STATCOM.

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C. *TRANSIENT STABILITY CONSTRAINTS*

For simplicity the criterion for transient stability is defined as the rotor angle deviation with respect to the centre of inertia (COI), and hence the inequality constraints of transient stability are formulated as [14]

$$\left|\delta_i - \delta_{coi}\right|_{\max} \le \delta_{\max} \qquad (21)$$

Where $|i - coi|$ corresponds to the maximum roto angle deviation of *i*_th generator from COI, and δmax is the maximum allowable rotor angle deviation.
The setting of δmax is often based on operational experience. Most utilities would have it set to 100°–120° to allow the system to have sufficient stability margin.

Where δ_{max} is set to 100°

IV. CASE STUDY AND DISCUSSIONS

The effectiveness of the proposed method is tested on the IEEE-30 bus power system. The single line diagram of the system is shown in Fig. 2. The total load for the operating condition considered is 283.4 MW and 126.2 MVAR.

The total fuel cost obtained from the MatPower package, which is considered as the base case without transient stability constraints. A three phase to ground fault at bus 2 and cleared by tripping line 2–5 at 0.3 s.

Power System Toolbox is used to perform time-domain transient stability simulations for determining the variation of the generator angles.

From table (row 2) it was observed that, when transient stability constraints were not considered (case1), the fuel cost was obtained optimal 984.34 $/h. However with this generation schedule, it was found that system transient stability was lost following the fault disturbance at bus 2. Clearly the network cannot be operated in this way since security of the network was violated. In order to secure operation of the power system, TSCOPF must therefore be considered (case2). From table (row 3) it can be seen that, to achieve transient stability (case2), there is substantial change in the generation schedule to meet the transient stability constraints as compared with the generation schedule in case1 (row 2). The active power loading of generator 2 is reduced from 80 MW (case1) to 60 MW (case2) while generator 1, 3, 4, 5

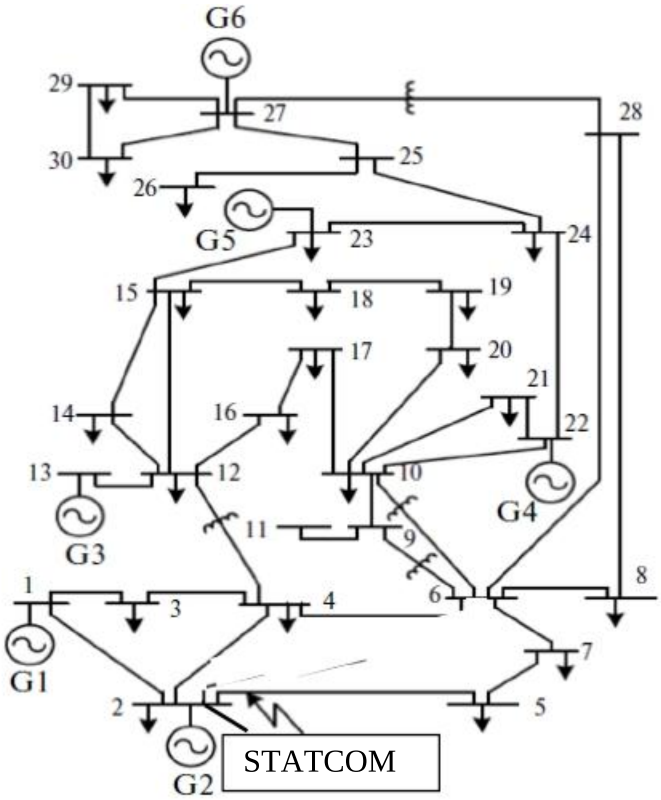

Fig. 2 IEEE 30-bus system one-line diagram

increases from 65, 35.53, 28.74 and 26.11 MW (case1) to 78, 40, 30.68, and 27.02 MW (case2) respectively. A consequence of satisfying the transient stability constraints is that of increasing fuel cost from 984.34 $/h (case1) to 998.43 $/h (case2) as shown in table (column 8).

The study in case 2 shows that, when the load demand is specified, the system without STATCOM can operate with transient stability being maintained for the fault disturbances considered but fuel cost is increased. In order to investigate the contribution of the STATCOM for minimum generation cost and remain transiently stable of power system following the fault disturbances considered, the load demand used in cases 1 and 2 is modified, and now has the total value of 299.2 MW (active power at bus 5 is increased from 94.2 MW to 110 MW).

Simulation results base on OPF with transient stability constraints and STATCOM installation in bus 2 is given in table (row 4). These simulation results demonstrate the effectiveness of STATCOM in improving system operation. Proper use of STATCOM gives better results in terms of OPF solution and also ensures system transient stability following the fault disturbance, therefore enhancing the system dynamic security.

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TABLE I
Optimization results for IEEE 30_bus system

Case	Pg1 Mw	Pg2 Mw	Pg3 Mw	Pg4 Mw	Pg5 Mw	Pg6 Mw	Fuel Cost $/h
Cas1	65	80	35.53	28.74	26.11	55	984.3
Cas2	78	60	40	30.68	27.02	55	998.4
Cas3	78.3	75	40	30.20	27.30	55	1062

V. CONCLUSIONS

The development of the modern power system has led to an increasing complexity in the study of power systems, and also presents new challenges to power system stability, and in particular, to the aspects of transient stability. Transient stability control plays a significant role in ensuring the stable operation of power systems in the event of large disturbances and faults, and is thus a significant area of research. Although the base OPF provides a dispatch that respects the physical and operational limitations, it did not guarantee the transient stability of the system after the fault has been cleared. Incorporating the transient stability constraints into the OPF to limit the value of the rotor angle allowed us to ensure that the system would be transiently stable following the fault.

This paper investigates the improvement of transient stability with OPF using STATCOM which is an effective FACTS.

Simulations are carried out in Matlab environment with STATCOM to analyze the effects STATCOM on transient stability performance of the system. The transient stability of the system is compared with the presence of STATCOM in the system. The simulation results demonstrate the effectiveness of the proposed STATCOM on transient stability improvement with OPF.

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