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A Review on Transient Stability Constrained Optimal Power Flow

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ABSTRACT: Optimal power flow with transient stability constraints simultaneously considers static and dynamic constraints of the power system when operating variables will be optimize. It has become a widely adopted tool for power system preventive control against loss of synchronism. But due to the high non-linear nature of system dynamics, the solving of TSC-OPF is very difficult. In this literature transient stability of the system will be restore.

The single machine equivalent (SIME) method is used to perform two main important functions of TSC-OPF approaches: first, the power system transient stability analysis will be perform by SIME; second, SIME determines a stable one machine infinite bus equivalent rotor angular trajectory that is used as the stability constraint in TSC-OPF problem. In this way, the power system dynamic behavior determines the stability constraint by using SIME, at each iteration of the TSC-OPF method. Transient stability constraints are formulated by reducing the initial multi-machine model to a one-machine infinite-bus equivalent. This equivalent allows imposing angle bounds that ensure transient stability. At first, the mathematical model of TSC-OPF is formulated. Subsequently, the difficulties of solving TSC-OPF are identified. The detailed review and discussions are then given, covering their computation procedures, merits and demerits, and possible improvement directions.

KEYWORDS: Optimal power flow, single-machine equivalent, transient stability.

I.INTRODUCTION

Optimal power flow (OPF) is a well studied optimization problem in power systems. This problem was first introduced by Carpentier in 1962. The objective of OPF is to find a steady state operating point that minimizes the cost of electric power generation while satisfying operating constraints and meeting demand. The problem can be formulated as a nonlinear programming (NLP) problem, in which some constraints and possibly the objective function are nonlinear. Complexity of planning and operating modern power systems is continually increasing because of larger power transfers over longer distances, greater interdependence among interconnected systems, more difficult coordination, and complex interaction among various system controllers and less power reserves. These demands have forced systems to be operated closer to their dynamic security limits, such that instability has become a major threat for system operation. Security refers to the ability of the power system to withstand sudden disturbances with minimum loss of the quality of service [1].

If DSA (Dynamic Stability Assessment) determines that transient instability could take place when the power system is subjected to a probable contingency, then control actions need to be designed and applied preventively in order to avoid a partial or complete service interruption. Among different preventive control measures, generation rescheduling has been considered to be one effective control scheme to bring a vulnerable system into a secure state under transient stability constraints [2]. Though this idea is simple and intuitive, traditionally, the generation dispatch that steers the system to a secure equilibrium point is sought in a heuristic way, which may produce high operating costs and possible discrimination among market players [3]. Bearing this in mind, and trying to reconcile the conflict between economics and dynamic security requirements in power system operation, it has been proposed to include transient stability constraints into the optimal power flow (OPF) model [4], thus creating transient stability-constrained OPF (TSC OPF) techniques. The resulting model is extended to consider multiple contingencies. The number of constraints is significantly reduced by using the reduced admittance matrix in [5].

TSC-OPF consists of an iterative procedure of two main steps. First, from a given initial equilibrium point, transient stability analysis is carried out to determine if the system is stable under a set of contingencies. In case a contingency (or more) could make the system unstable, simulation results are used in order to compute a set of stability constraints.

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Second, transient stability constraints are included into the optimal power flow model, which determines a new improved operating condition. Stability analysis is performed again to check that the new operating condition has already been stabilized. This two-step iterative process is repeated iteratively until reaching an equilibrium point that satisfies transient stability constraints.

The transient stability assessment is solved and the results are used to determine a bound on the active power generation of a group of “critical machines” within the OPF problem [6]. The transient stability assessment can be done through a Simulink model. The time-domain simulation allows taking into account the full system dynamic model and consists in checking that inter-machine rotor angle deviations lie within a specific range of values[7]. The original multi-machine model to a two-machine model using the concept of Single Machine Equivalent (SIME). This two machine model is further reduced to a one-machine infinite-bus (OMIB) equivalent, following well-established procedures[8]. A bound calculated through appropriate time-domain simulations is imposed on the angle of the single equivalent machine to ensure transient stability.

II.SYSTEM MODEL AND TRANSIENT STABILITY CRITERION

A. Synchronous Machine Model

In this paper, we use the classical model of the synchronous machine since it allows reducing the computational burden of the proposed approach while maintaining reliable results. Thus, the swing equations for the machine are represented by a constant emf behind a transient reactance [6].

$$\dot{\delta}_i=\Omega_b\left(\omega_i-1\right), \qquad \forall i \in G \tag{1}$$

$$\dot{\omega}_i = \frac{1}{M_i}\left(P_{Gi}-P_{ei}\right), \qquad \forall i \in G \tag{2}$$

In (2), the mechanical power is considered constant, i.e., fast valving or generator power shedding are not considered. If the loads are approximated as constant impedances, the equivalent load admittance at bus n is

$$Y_{Dn} = \frac{P_{Dn}}{V_n^2} - j\,\frac{Q_{Dn}}{V_n^2} \tag{3}$$

and the original network can be transformed into an equivalent reduced network whose nodes are only the internal generator nodes [9]. The admittance matrix of the reduced network is called reduced admittance matrix and can be used to define the electrical power of the generators. Hence, the electrical power P_{ei} in (2) can be written as

$$P_{ei}=E'_i\sum_j E'_j\left[B_{ij}\sin\left(\delta_i-\delta_j\right)+G_{ij}\cos\left(\delta_i-\delta_j\right)\right] \tag{4}$$

The proposed formulation allows reducing the number of variables and constraints of the OPF model, because bus voltage magnitudes and phases as well as the equations of current injections at network buses are not needed in (4).

B. Transient Stability Criterion

The transient stability criterion used in this paper is based on the SIME method [8]. SIME is a transient stability analysis technique based on a simple but effective and well-proved technique. For each step of the time-domain simulation, SIME divides the multi-machine system into two groups, 1) the group of machines that are likely to lose synchronism (critical machines)and 2) all other machines (noncritical machines). The maximum difference between two adjacent rotor angles, say, indicates the frontier between the two machine groups, as follows. All generators whose rotor angles are greater than are part of the critical machine group, while all generators whose rotor angles are lower than are part of the noncritical machine group. These two groups are replaced by an OMIB equivalent system, whose transient stability is determined by means of the equal-area criterion (EAC). Finally, SIME establishes a set of stability conditions based on the equivalent OMIB parameters and on the EAC. A detailed description of the SIME method is given in [8]. If the simulation is unstable, SIME provides information about which are the critical machines, the time and the rotor *unstable* angle for which the instability conditions are reached. Similarly, if a simulation is first-swing stable, SIME provides the time and the rotor return angle for which the OMIB equivalent meets the first-swing stability conditions. We use SIME criteria to define transient stability limits in the OPFproblem.

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III. TSC-OPF PROBLEM FORMULATION

A. Objective Function

If the TSC-OPF is used as a dispatching tool, the objective function is

$$F\left(P_{Gi}\right) = \sum_{i \in G} \left(\alpha_i + \beta_i P_{Gi} + \gamma_i P_{Gi}^2\right) \tag{5}$$

Where, P_{Gi} is the active power generation of generator i and $\alpha_i, \beta_i, \gamma_i$ are its cost coefficient.

The active generation powers P_{Gi} is defined as

$$P_{Gi} = P_{Gi}^{A} + \Delta P_{Gi}^{up} - \Delta P_{Gi}^{down}, \qquad \forall i \in G \tag{6}$$

Where P_{Gi}^{A} represents the base case active power of generator i .

The power adjustment needs the following additional constraints:

$$\Delta P_{Gi}^{up} \geq 0, \Delta P_{Gi}^{down} \geq o \qquad \forall i \in G \tag{7}$$

Subject to

B. Pre-contingency power flow equation as

$$P_{Gn} - P_{Dn} = \sum_{m \in \theta_n} P_{nm}(\square) \qquad \forall n \in N \tag{8}$$

$$Q_{Gn} - Q_{Dn} = \sum_{m \in \theta_n} P_{nm}(\square) \qquad \forall n \in N \tag{9}$$

Where,

$$P_{Gn} = \sum_{i \in G_n} P_{Gi} \qquad \forall n \in N \tag{10}$$

$$Q_{Gn} = \sum_{i \in G_n} Q_{Gi} \qquad \forall n \in N \tag{11}$$

C. Technical Limit

The power production is limited by capacity of generator as

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max} \qquad \forall i \in G \tag{12}$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max} \qquad \forall i \in G \tag{13}$$

The bus voltage magnitude must be within operating limit

$$V_n^{\min} \leq V_n \leq V_n^{\max} \qquad \forall n \in N \tag{14}$$

The current must be bellow thermal limit

$$I_{nm}(\square) \leq I_{nm}^{\max} \tag{15}$$

D. Initial value of machine rotor angle, rotor speed and electromotive forces are

$$\frac{E_i^{/} V_n \sin\left(\delta_i^0 - \theta_n\right)}{x_{di}^{/}} - P_{Gi} = 0 \qquad \forall i \in G_n \tag{16}$$

$$\frac{E_i^{/} V_n \cos\left(\delta_i^0 - \theta_n\right) - V_n^2}{x_{di}^{/}} - Q_{Gi} = 0 \qquad \forall i \in G_n \tag{17}$$

Since, Pre-fault is a steady state condition

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$$\omega_i^0 = 1 \qquad \forall i \in G \qquad (18)$$

E. Discrete Swing Equation

The swing equation (1) and (2) are discretized using trapezoidal rule as

$$\delta_i^{t+1} = \delta_i^t - \frac{\Delta t}{2}\omega_b\left(\omega_i^{t+1} + \omega_i^t - 1\right) \quad \forall t \in T, \forall i \in G \qquad (19)$$

$$\omega_i^{t+1} + \omega_i^t - \frac{\Delta t}{2}\frac{1}{M_i}\left(P_{Gi} - P_{ei}^{t+1} + P_{Gi} - P_{ei}^t\right) = 0 \quad \forall t \in T, \forall i \in G \qquad (20)$$

Where,

$$P_{ei}^t = E_i^/ \sum_{j\in G} E_j^/ \left[B_{ij}^t \sin\left(\delta_i^t - \delta_j^t\right) + G_{ij}^t \cos\left(\delta_i^t - \delta_j^t\right)\right] \qquad (21)$$

F. Transient stability limit

$$\delta^t \le \delta^{\max}, \qquad \forall t \in T \qquad (22)$$

Where T is as small as possible to reduce computing time but larger than the instability time as defined by the SIME method.

The equivalent rotor angle is computed as

$$\delta^t = \frac{1}{M_c}\sum_{i\in G_C} M_i \delta_i^t - \frac{1}{M_{nc}}\sum_{i\in G_{Nc}} M_i \delta_i^t \qquad (23)$$

Where,

$$M_c = \sum_{i\in G_C} M_i \;, M_{nc} = \sum_{i\in G_C} M_i \qquad (24)$$

G. Other constraints are

$$-\Pi \le \theta_n \le \Pi \qquad \forall n \in N \qquad (25)$$

$$\theta_{ref} = 0. \qquad (26)$$

IV. PROCEDURE TO ENSURE TRANSIENT STABILITY

Converting the whole time-domain simulation of the system transient stability model into a set of algebraic equations results in a very large number of equations to be included in an OPF. Solving such nonlinear OPF problem may require prohibitive computing times and prohibitive memory size, and may lead to convergence issues. To reduce the number of constraints, we use the reduced admittance matrix and constrain the OMIB equivalent trajectory only during the first swing of the system. The latter allows including the discretized transient stability equations (19)–(20) and (22) only for a few seconds after the fault occurrence.

The proposed procedure is as follows.

1) Base case solution. The base case solution can be obtained from an OPF problem without considering transient stability limit.

2) *Contingency analysis*. The contingency analysis consists in identifying, from a set of credible contingencies, the ones that lead the system to instability. This identification is carried out by means of a time-domain simulation complemented by SIME using a technique similar to the one in [8]. For first-swing unstable contingencies, SIME provides the sets of critical and noncritical machines and the instability limit (δ_u) for the OMIB equivalent. Equations (22) and (24) incorporate this information.

3) *Solve the TSC-OPF problem*. The OPF problem described in Section III is solved and the new generating powers and bus voltages are computed.

4) *Check the new solution*. A time-domain simulation that includes SIME is solved for the new operating point obtained at step 3. This simulation is necessary to check the transient stability of the new operating point. Three different cases can be encountered.

a) The system is stable and the procedure stops.

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b) The system is first-swing unstable. This is due to the fact that the reduced admittance Y_{bus} used in the optimization problem has been calculated for the initial solution that exhibits different voltage values than the solution obtained at step 3 [see (3)]. Thus, the reduced admittance matrix is updated and the transient stability limit is fixed to the new value of δ_u . The procedure continues at step 3.

c) The system is multi-swing unstable. In this case, the OMIB equivalent has a return angle δ_r in the first swing. However, after some cycles, the system loses synchronism. The return angle value δ_r is used to define the new transient stability limit $\delta_{\max}$ .In order to avoid multi-swing phenomena, $\delta_{\max}$ is set to $\delta_r - \Delta\delta$ .i.e., $\delta_{\max}$ is fixed to a value smaller than δ_r . The value of the decrement $\Delta\delta$ is defined based on a heuristic criterion. Finally, the reduced admittance matrix Y_{bus} is updated. The procedure continues at step 3. The flowchart depicted in Fig. 1 illustrates the proposed procedure.

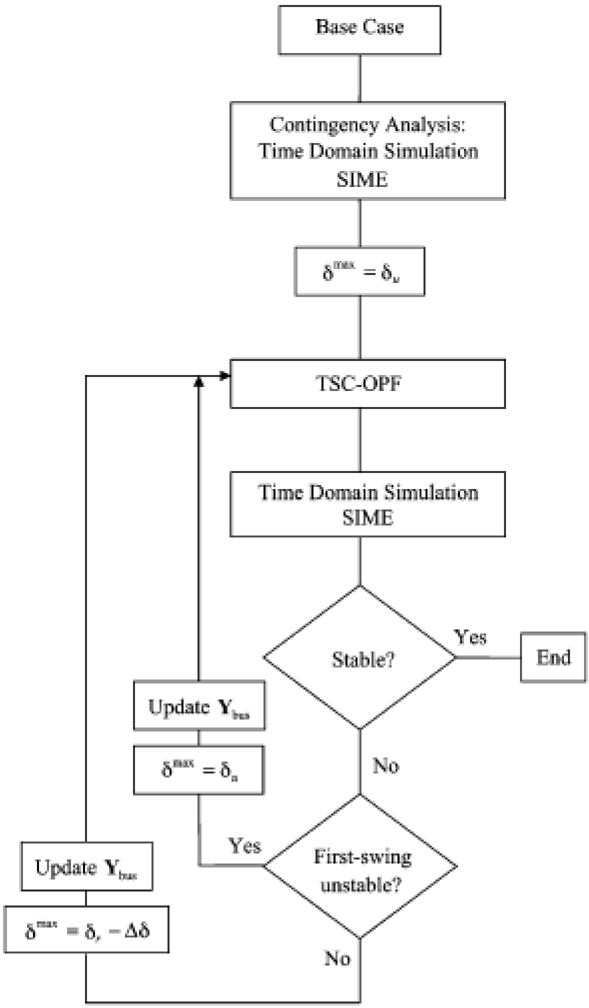

Fig.1 Flow Chart of Proposed Procedure.

V. CONCLUSION

Transient stability-constrained optimal power flow (TSC-OPF) can simultaneously consider the static and dynamic constraints of the power system when optimizing the system variables. It has become a widely adopted tool for power system preventive control against blackouts triggered by transient instability. But due to the high non-linear inherence

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of system dynamics, the solving of TSC-OPF is very tricky. This paper conducts a comprehensive review on the methods, trying to provide systematic insight into this area.

In this transient stability of a system will be restored. It is based on OPF model with transient stability constraints. This constraints are obtained from SIME method and ensure transient stability of system against disturbance such as faults on transmission line. An advantage of the proposed technique is the fact that additional details can be incorporated by taking into account alternative device models and/or adding different transient stability constraints. These modifications and their effects on the accuracy of the results will be investigated in future work on this topic.

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