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Solving Multi-Objective Voltage Stability Constrained Power Transfer Capability Problem using Evolutionary Computation

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Abstract

Competitive market forces and the ever-growing load demand are two of the key issues that cause power systems to operate closer to their system stability boundaries. Open access has since introduced competition and therefore promotes inter-regional electrical power trades. However, the economic flows of electrical energy between interconnected regions are usually constrained by system physical limits, e.g. transmission lines capacity and generation active/reactive power capability etc. As such, there is a limitation to the capacity of electrical power that regions can export or import. This maximum allowable electrical power transfer is normally referred to as Total Transfer Capability (TTC). It is critical to understand that TTC does not necessarily represent a safe and reliable amount of inter-regional power transfer as one or more operational limits are usually binding when quantifying TTC. Hence, it is of interest that power system stability issues are being considered during power transfer capability assessment in order to provide a more appropriate and secure power transfer level.

The aim of this paper is to formulate an Optimal Power Flow (OPF) algorithm, which is capable of evaluating inter-area power transfer capability considering mathematically-complex voltage collapse margins. Through a multi-objective optimization setup, the proposed OPF-based approach can reveal the nonlinear relationships, i.e. the pareto-optimal front, between transfer capability and voltage stability margins. The feasibility of this approach has been intensively tested on a 3-machine 9-bus and the IEEE 118-bus systems.

KEYWORDS: total transfer capability, particle swarm optimization, voltage stability

1. INTRODUCTION

Power system transfer capability as defined by the North American Electric Reliability Council (NERC) in 1996, refers to the ability of interconnected electric networks to safely deliver or transfer bulk electrical power from one area to another over all connecting transmission interfaces under specified system conditions. Available Transfer Capability (ATC) is a measure of the transfer capability remaining in the network for further commercial activity over and above already committed uses (NERC 1996); and determining of Total Transfer Capability (TTC) is the key component in the context of ATC computation (NERC 1996; PSERC 2001).

At present, more commonly-used ATC/TTC methods include (NERC 1996; PSERC 2001): (i) repeated power flow (RPF) (Gravener & Nwankpa 1999; Ou & Singh 2002); (ii) continuation power flow (CPF) (Ajarapu & Christy 1992; Ejebe et al. 1998; Chiang et al. 1995; Tong 2000); (iii) optimal power flow (OPF) (Bresesti et al. 2002; Luo et al. 2000); and (iv) DC load flow utilizing linear sensitivity factors (Ejebe et al. 2000). These approaches are usually performed in a simplified manner, and thus with limited consideration of power system stability constraints. It is evident that an overly-optimistic measure of inter-area power transfer capability can sometimes lead to system instability issues (NERC 1996; PSERC 2001), and thus it is vital to ensure that the system operating point, prior to a large power transfer dispatch, is always remained well within its stability limits.

Many of the key blackout events in the past, e.g. in North America, Europe and Australia, have been found to be associated with some form of voltage instability issues, which have consequently resulted in system-wide voltage collapses. Hence, it is crucial that Voltage Stability Assessment (VSA) is, at least, performed during ATC/TTC assessment for more secure operation of power systems. Voltage instability issues usually occur in power systems, which are heavily-loaded, faulted and/or have reactive power shortages (IEEE/PES 2002). As it is generally accepted that voltage stability margins can actually reflect the overall stability margins of a power system, there are some interests in formulating voltage stability constraints into traditional OPF problems. Extensive studies have since being done on Voltage Stability Constrained OPF (VSC-OPF) problems based on an interior point optimization method, e.g. (Milano et al. 2003; Rosehart et al. 2003).

Unfortunately due to the complexity of power system stability problems, the resultant solution spaces when solving inter-area power transfers together with system stability boundaries may sometimes become unusually complicated. As such, traditional optimization techniques, i.e. gradient-based methods, can sometimes fail or encounter numerical difficulties with objective functions, which

are not always differentiable or convex (Dong et al. 1998; Goh et al. 2007). In contrast, Evolutionary Computation (EC) techniques, e.g. Particle Swarm Optimization (PSO) or Differential Evolution (DE), are powerful population-based searching algorithms that are well-suited in obtaining global optimal solutions regardless of complex solution spaces, i.e. non-convex, uni-modal or multimodal etc. The beauty of EC techniques over traditional methods is that equivalent or even superior solutions can be obtained without the need of complex differentiation of objective functions and constraints, and hence making the implementation process much easier.

The primary aim of this paper is to formulate an OPF based approach, which is capable of overcoming the limitations of traditional optimization techniques, for investigating inter-area power transfer capability and its associated voltage collapse margins. The proposed approach can be modelled as a multi-objective optimization problem. It can be used to assist system operators and planners to visualize the nonlinear relationships between power transfer levels and voltage stability margins by the means of the pareto-optimal sets. The information provided by these pareto-optimal sets can be useful for various power system operation and planning purposes.

The remaining of this paper is structured as follows: Section 2 reviews the theoretical background of power system voltage stability; Section 3 formulates the multi-objective optimization model used to study voltage stability constrained inter-area TTC; Section 4 presents a brief introduction on PSO; Section 5 includes some case examples with detailed discussions; and finally, Section 6 summarizes the major contributions of this paper and provides recommendations for future work.

2. POWER SYSTEM VOLTAGE STABILITY ASSESSMENT

As mentioned previously, high power transfer levels across interconnected networks usually compromise power system stability (NERC 1996; PSERC 2001); and thus it is crucial that when assessing ATC/TTC levels, system stability issues are, at least, being analyzed. In this paper, the authors emphasize mainly on voltage stability issues since it has strong ties to the maximum deliverable power theorem between generation and loads, and the overall stability of power systems. This section briefly describes the fundamental background theories of power system VSA, and it commences with the introduction of a power system model used for stability analysis.

2.1 POWER SYSTEM MODELLING

The power system model used in stability studies can be expressed by the following differential-algebraic equations (DAE) (IEEE/PES 2002; Goh et al. 2007; Dong et al. 2005; Makarov et al. 1998; Makarov et al. 2000):

$$\begin{aligned}\dot{x} &= f(x_s, x_a, \lambda) \\ 0 &= g(x_s, x_a, \lambda)\end{aligned}\quad (1)$$

where x_s is a vector of system state (differential) variables, x_a is a vector of algebraic variables, and λ is a vector of bifurcation parameters that varies slowly over time, so that the system moves from one equilibrium point to another towards bifurcations.

In general, the equilibrium points of the dynamic model, as shown by Equation (1), can be represented by a simplified model, which can then be expressed as follows (IEEE/PES 2002; Goh et al. 2007; Dong et al. 2005; Makarov et al. 1998; Makarov et al. 2000):

$$\begin{bmatrix} \Delta P(u, \lambda) \\ \Delta Q(u, \lambda) \end{bmatrix} = F(u, \lambda) = 0 \quad (2)$$

where Equation (2) is a set of non-linear equations of complex power mismatches at system buses, i.e. the conventional load flow equations augmented with the bifurcation parameters λ ; $F(u, \lambda)$ is a subset of the full system as shown by Equation (1); and u usually defines V and δ , i.e. the phasor bus voltages in load flow analysis.

2.2 DETERMINING VOLTAGE COLLAPSE MARGINS

In many instances, voltage instability events have been found to coincide with saddle-node bifurcations. Therefore, by locating these bifurcation points, one can easily determine the voltage collapse margins by solving the following equations (IEEE/PES 2002; Goh et al. 2007; Dong et al. 2005; Makarov et al. 1998; Makarov et al. 2000):

$$\begin{aligned}
 F(u, \lambda) &= 0 \\
 D_u F(u, \lambda)^T w &= 0 \\
 \|w\|_\infty &= 1
 \end{aligned} \tag{3}$$

which correspond to the system steady-state equations, the singularity conditions at the collapse point, and the non-trivial condition. These equations can be solved using the Newton-Raphson-Seydel method or optimization approaches (Dong et al. 2005; Makarov et al. 1998; Makarov et al. 2000; Canizares 1998), or even EC techniques as shown in (Dong et al. 1998; Goh et al. 2007). The voltage collapse margin can be obtained by computing the distance towards voltage collapse boundaries from a stable equilibrium operating point as denoted by λ , i.e. $\Delta\lambda = \lambda_* - \lambda$ (IEEE/PES 2002; Dong et al. 1998; Dong et al. 2005; Makarov et al. 1998; Makarov et al. 2000; Canizares 1998). In this paper, this voltage stability margin, $\Delta\lambda$, will be used to evaluate voltage stability when quantifying inter-area power transfer capability, i.e. ATC/TTC levels.

3. MULTI-OBJECTIVE POWER TRANSFER CAPABILITY ASSESSMENT

Although the introduction of the OPF problem was dated back to as early as in the 1960s (Dommel & Tinney 1965; Huneault & Galiana 1991), it is still under very active research and development. The OPF problem is very versatile, and it can be formulated to solve many power system optimization problems including power transfer capability. This section gives an overview of an OPF formulation used to investigate inter-area active power transfers.

3.1 A BASIC OPF-BASED TTC PROBLEM (OPF-TTC)

Determining TTC can be seen as a nonlinear optimization problem, which can be represented using a conventional OPF model as follows (NERC 1996; PSERC 2001):

$$\begin{aligned}
 \max \quad & f(x) \\
 \text{s.t.} \quad & g(x) = 0 \\
 & h(x) \leq 0
 \end{aligned} \tag{4}$$

where $f(x)$ is the objective function to be optimized; $g(x)$ is the set of equality constraints; $h(x)$ is the set of inequality constraints; and x is a vector of system

variables which, in this paper, refers to the nodal active and reactive power injections and the bus phasor voltages. Note that additional control variables, e.g. transformer taps, shunt and series reactive power compensation devices etc may also be included in this OPF-TTC model, to improve inter-area transfer capability and voltage stability (Goh et al. 2006).

The objective is to maximize inter-area active power flows across all connecting transmission interfaces, hence $f(x)$ can be shown as follows:

$$f(x) = \sum_{m \in R, n \in S} P_{mn} \quad (5)$$

where m denotes the set of buses in the sending area (S) and n denotes the set of buses in the receiving area (R). The equality constraints, as denoted by $g(x)$, are basically the load flow equations, which can be expressed as follows:

$$\begin{aligned} P_i - \sum_{j \in N} V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_i - \delta_j) &= 0 \\ Q_i - \sum_{j \in N} V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_i - \delta_j) &= 0 \end{aligned} \quad (6)$$

where N is the set of all the buses in the system; V_i , V_j and δ_i , δ_j are the voltage magnitudes and angles of bus i and bus j respectively; Y_{ij} and θ_{ij} are the magnitude and angle of the ij -th element in the bus admittance matrix Y . The inequality limits $h(x)$ considered during TTC computation in this paper include, but not limited to:

$$P_{Gi_{\min}} \leq P_{Gi} \leq P_{Gi_{\max}} \quad (7)$$

$$Q_{Gi_{\min}} \leq Q_{Gi} \leq Q_{Gi_{\max}} \quad (8)$$

$$V_{i_{\min}} \leq V_i \leq V_{i_{\max}} \quad (9)$$

$$\delta_i - \delta_{ref} \leq \Delta\delta_{\min}, \quad i \neq ref \quad (10)$$

$$S_{ij} \leq S_{ij_{\max}} \quad (11)$$

where Equations (7) and (8) are the generator i active and reactive power capability respectively; Equations (9) and (10) are the phasor bus voltage limit at bus i ; and lastly Equation (11) represents the thermal limits of transmission line connecting bus i and j .

3.2 OPF-TTC WITH VOLTAGE STABILITY CONSTRAINTS (VSC-TTC)

The basic OPF-TTC problem, as shown by Equation (4) is slightly modified to a multi-objective optimization setup, using the weighted-sum method (Cvetkovic & Parmee 2002; Deb 2001), to include voltage stability constraints as in (Milano et al. 2003; Rosehart et al. 2003; Canizares 1998):

$$\begin{aligned}
 \max \quad & w_1 f(x) + w_2 \Delta\lambda \\
 \text{s.t.} \quad & g(x) = 0 \\
 & h(x) \leq 0 \\
 & g(u, \lambda) = 0
 \end{aligned} \tag{12}$$

where $f(x)$ is the first objective function to maximize TTC shown previously by Equation (5); $\Delta\lambda = \lambda_* - \lambda$ is the second objective, representing a measure of the margin between the current operating point and the voltage collapse point; $g(x)=0$ is the set of equality constraints shown previously by Equation (6); $h(x)\leq 0$ is the set of inequalities shown previously by Equations (7) to (11); $g(u, \lambda)=0$ is the set of equalities shown previously by Equation (3); w_1 and w_2 are the weighting factors used to denote the optimization emphasis on both objectives. Note that $w_1 \in [0,1]$, $w_2 \in [0,1]$ and $w_1 + w_2 = 1$ (Cvetkovic & Parmee 2002).

A major limitation of the weighted-sum method is that proper normalization of objectives is required in order to obtain more precise solutions. To avoid solution inaccuracies, the ε -constraint method (Deb 2001) is used to formulate the VSC-TTC problem, as shown by Equation (12) in this paper. It transforms one of the objectives into a soft constraint, and thus resulting in typical single-objective optimization problem, which can then be expressed as follows (Milano et al. 2003; Rosehart et al. 2003):

$$\begin{aligned}
 \max \quad & f(x) \\
 \text{s.t.} \quad & g(x) = 0 \\
 & h(x) \leq 0 \\
 & g(u, \lambda) = 0 \\
 & \lambda_* - \lambda \geq \Delta\lambda_{\min}
 \end{aligned} \tag{13}$$

where $\lambda_* - \lambda \geq \Delta\lambda_{\min}$ is the objective-turned-constraint that guarantees a minimum distance to voltage collapse from the current operating point, the symbol * denotes the voltage collapse point conditions, i.e. saddle-node bifurcation has occurred. Without normalization difficulties, the ε -constraint method is capable of identifying the true pareto-optimal sets (Deb 2001). In this paper, these pareto-optimal sets allow easier visualization of the nonlinear relationships between power transfer capability and its associated voltage collapse margins (Cvetkovic & Parmee 2002).

4. PARTICLE SWARM OPTIMIZATION

The OPF model used to investigate voltage stability constrained inter-area TTC (VSC-TTC), as shown in previous section, involves very complicated implementation of the differentials of objectives and constraint equations. Most importantly, the resultant solution spaces of the VSC-TTC problem may sometimes become unusually complex that traditional methods would fail or encounter numerical difficulties with the differential equations (Dong et al. 1998; Goh et al. 2007). In order to overcome major limitations faced by many traditional methods, EC techniques can be reliable alternatives in many complex engineering optimization applications. In this paper, PSO is used as the EC optimization solver for the VSC-TTC problem as defined in Equation (13). It should be noted that other latest EC methods such as DE can also be applicable, however it is not the purpose of this paper to elaborate on these issues.

The main benefits of PSO includes: (i) easy to implement; (ii) computationally inexpensive; (iii) capability to locate global optimal solutions; (iv) ability to handle complex solution spaces etc. PSO, which is introduced in 1995 (Kennedy & Eberhart 1995; Eberhart & Shi 2004), is a population-based search algorithm which exhibits good convergence characteristics. It has since been successfully applied to solve many complex power system optimization problems (AlRashidi & El-Hawary 2009; Heo et al. 2006; Vlachogiannis & Lee 2006).

The remaining of this section provides a brief introduction on the concepts of PSO. If $X_i = (x_{i1}, x_{i2}, \dots, x_{id})$ and $V_i = (v_{i1}, v_{i2}, \dots, v_{id})$ are the position vector and the velocity vector respectively in a multi-dimensional (d dimensions) search space, then according to a user-defined fitness function, whereby $P_i = (p_{i1}, p_{i2}, \dots, p_{id})$ is the *pbest* vector and $P_{gd} = (p_{g1}, p_{g2}, \dots, p_{gd})$ is the *gbest* vector, i.e. the fittest particle of P_i , updating new positions and velocities for the next generation can be determined by the following equations (Kennedy & Eberhart 1995; Shi & Eberhart 1998):

$$\begin{aligned} v_{id} &= v_{id} + c_1 \times rand1(.) \times (p_{id} - x_{id}) + c_2 \times rand2(.) \times (p_{gd} - x_{id}) \\ x_{id} &= x_{id} + v_{id} \end{aligned} \quad (14)$$

where c_1 and c_2 are constants known as acceleration coefficients; $rand1(.)$ and $rand2(.)$ are two different uniformly distributed random numbers in the range of $[0,1]$; w is the inertia weight, which can be expressed as follows (Shi & Eberhart 1999):

$$w = (w_i - w_f) \times \frac{(iter_{max} - iter)}{iter_{max}} + w_f \quad (15)$$

where w_i and w_f are the initial and final values of the inertia weight respectively; $iter$ is the current PSO generation number, and $iter_{max}$ is the maximum allowed PSO generations.

5. NUMERICAL EXAMPLES

This section includes two case examples using a simple 3-machine 9-bus system from Anderson and Fouad (1977), and a larger scale IEEE 118-bus system from the Power Systems Test Case Archive UWEE webpage (2010). The proposed OPF technique is applied to investigate TTC and its nonlinear relationship with voltage collapse margins. From the trials and sampling of the PSO algorithm, useful statistical information can be extracted, which can assist system operators and planners to define an appropriate and secure TTC level. The parameters used for the PSO simulations are decided to be as follows:

- Population size = 30
- Maximum allowed generation: $iter_{max} = 100$
- Acceleration coefficients: $c_1 = c_2 = 2.0$
- Inertia weights: $w_i = 0.9$, $w_f = 0.4$
- Maximum velocity: $v_{id_{max}} = \frac{x_{id_{max}}}{2}$
- Minimum velocity: $v_{id_{min}} = -v_{id_{max}}$

Take note that PSO is terminated only if the maximum number of generation is reached.

5.1 3-MACHINE 9-BUS SYSTEM

The 9-bus system used consists of 3 generators and 3 loads as shown in Figure 1. By solving the problem shown by Equation (3), the distance to voltage collapse is determined to be $\Delta\lambda = 1.4854$ [pu] from the base case operating conditions of the 9-bus system. This $\Delta\lambda = 1.4854$ [pu] is the additional loading capability/margin of the system before voltage instability occurs. It is also widely-used as a voltage collapse indicator/index (IEEE/PES 2002). Take note that the distance to voltage collapse $\Delta\lambda$ in this paper is calculated as $\Delta\lambda = \lambda_* - \lambda$, whereby λ is the base case loading set to 1.0 [pu].

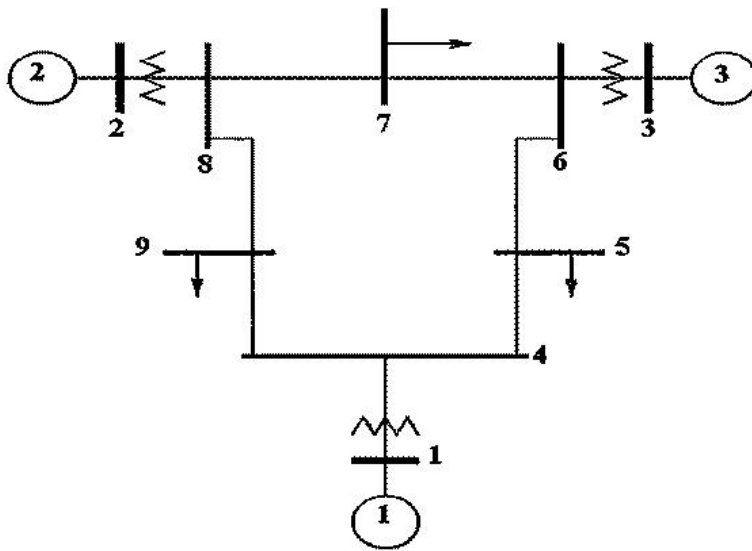


Figure 1. 3-machine 9-bus system

5.1.1 TTC WITHOUT CONSIDERATION OF VOLTAGE STABILITY CONSTRAINTS

As defined by the NERC, evaluating TTC can be seen as a nonlinear constrained optimization problem, whereby the objective is to maximize inter-area active power transfers (NERC 1996; PSERC 2001). If the 9-bus system is divided into 2 areas with tielines 5-6 and 4-9 (See Figure 1), then according to Equations (4) and (5), the resultant TTC problem can be expressed as follows:

$$\max \quad \text{fitness} = P_{5-6} + P_{4-9} \quad (16)$$

where P_{5-6} and P_{4-9} are the total active power flows of the connecting tielines.

The OPF-TTC problem, as shown by Equation (16), which is used to compute maximal power transfers, is firstly solved without voltage stability consideration for 50 PSO trials. Table 1 displays the optimal settings of AVRs and the active power (PG) outputs of generators 2 and 3 from the best trial; and Table 2 presents the statistical information of TTC [MW] from the 50 trials. Note that μ and σ denote the mean and standard deviation of the 50 trials respectively. Figure 2 depicts the histogram from the statistics obtained from the PSO trials. The maximum TTC without voltage stability consideration is found to be 157.59 [MW].

AVR (Gen)	V [pu]	PG (Gen)	P [pu]
AVR 2	1.093	PG 2	0.1000
AVR 3	1.000	PG 3	0.6129

Table 1. Best Particle of 50 OPF-TTC trials

	Best	Worst	μ	σ
TTC [MW]	157.59	156.97	157.34	0.20

Table 2. Statistics of OPF-TTC (50 trials)

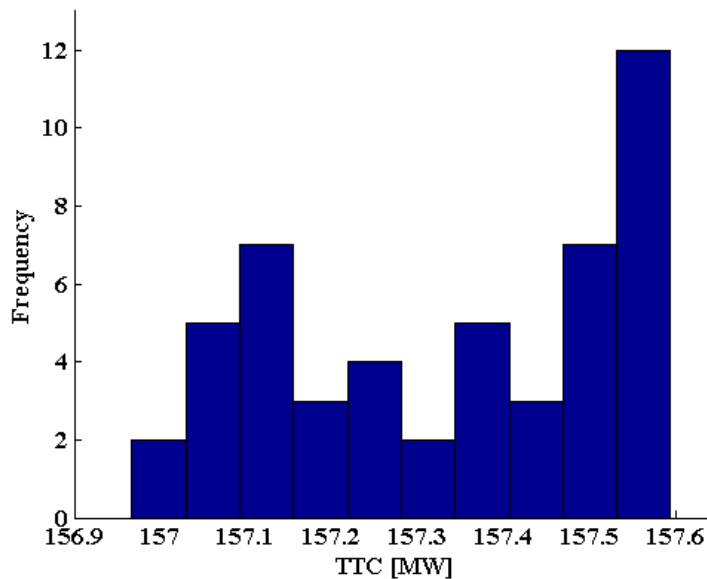


Figure 2. Histogram of TTC values [MW] (9-bus system)

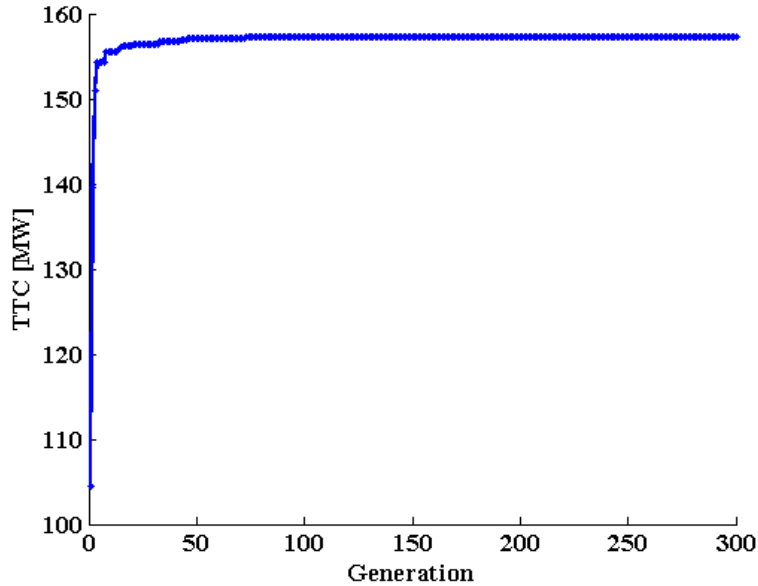


Figure 3. Convergence characteristics of PSO-based OPF-TTC (9-bus system)

The distance to voltage collapse from the maximal transfer conditions is then calculated to be $\Delta\lambda = 1.0363$ [pu]. Notice that by forcing the system to have a high power transfer level across tielines 5-6 and 4-9, the overall system stability is usually being compromised, i.e. the voltage collapse margin reduces from 1.4854 [pu] to 1.0363 [pu] under maximal transfer conditions as compared to the base case operating conditions. Figure 3 shows one of the convergence plots from the 50 OPF-TTC trials.

5.1.2 TTC CONSIDERING VOLTAGE STABILITY CONSTRAINTS

The proposed PSO-based OPF technique, as shown by Equation (13), is then applied to solve the VSC-TTC problem, as shown by Equation (16), considering a newly-added voltage stability constraint $\lambda_* - \lambda \geq \Delta\lambda_{\min}$, whereby it is set to a experimental value of 1.25 [pu]. This enforces the system operating point to have a voltage stability margin of at least 1.25 [pu] of the total system loads. Note that this constraint value is preference-based and is usually set by the system operator. Table 3 presents the optimal settings of the control variables; and Table 4 presents the statistical information of VSC-TTC [MW] from the 50 trials. Figure 4 shows one of the convergence plots from the 50 VSC-TTC trials, demonstrating the relatively good convergence of PSO to optimal or suboptimal solutions within 100 generations.

AVR (Gen)	V [pu]	PG (Gen)	P [pu]
AVR 2	1.100	PG 2	0.6353
AVR 3	1.100	PG 3	0.2502

Table 3. Best Particle of 50 VSC-TTC trials ($\Delta\lambda \geq 1.25$ [pu])

	Best	Worst	μ	σ
VSC-TTC [MW]	139.65	138.72	139.47	0.17

Table 4. Statistics of VSC-TTC (50 trials, $\Delta\lambda \geq 1.25$ [pu])

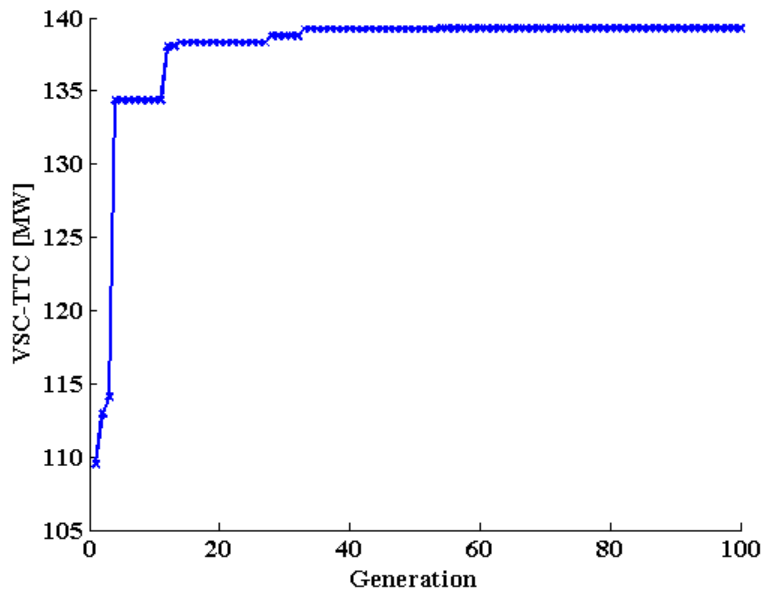


Figure 4. Convergence characteristics of PSO-based VSC-TTC (9-bus system)

Figure 5 presents a histogram of VSC-TTC when considering a voltage stability limit of $\Delta\lambda \geq 1.25$ [pu] from the PSO trials. The power-voltage (P-V) curves of bus 9 of the system, generated using Equation (2), are depicted in Figure 6. Bus 9 is chosen because it appeared to be the weakest bus in the system. Observe that the voltage collapse margin for the maximal transfer case (OPF-TTC) decreases significantly, which is probably due to the high power transfers across the two selected tielines. A voltage stability limit, $\lambda_* - \lambda \geq 1.25$ [pu], is then enforced into the proposed PSO-based VSC-TTC algorithm, as shown in Equation (13), thus forcing $\Delta\lambda$ to increase till 1.25 [pu].

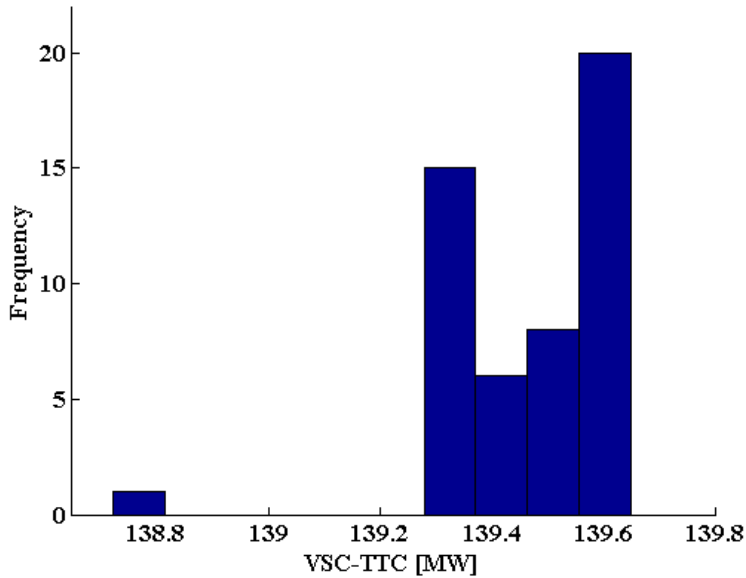


Figure 5. Histogram of VSC-TTC [MW] with $\Delta\lambda \geq 1.25$ [pu] (9-bus system)

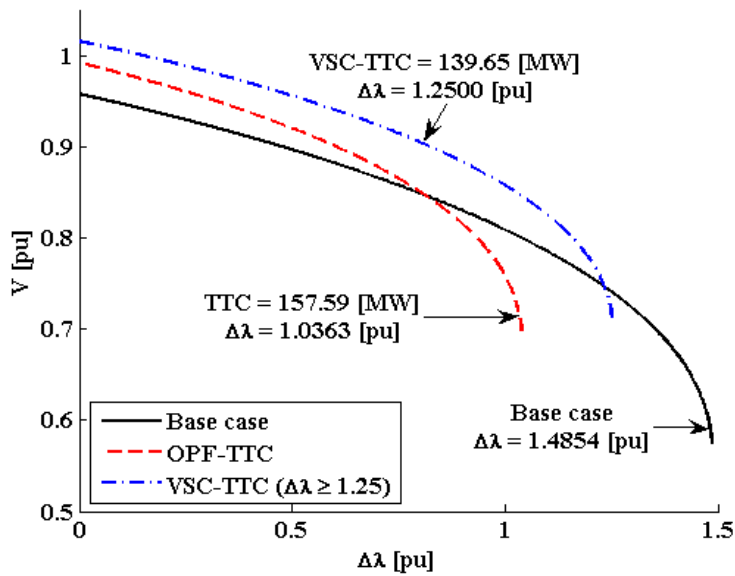


Figure 6. P-V curves of bus 9 (9-bus system)

Figure 7 is a plot consisting of optimal or suboptimal solutions, obtained from numerous trials, which estimates the pareto-optimal front relating TTC and $\Delta\lambda$. It can be plotted by varying the voltage stability limit $\Delta\lambda_{\min}$ over a feasible range, and then solving the resultant optimization problem for VSC-TTC. In this

paper, the voltage stability margin $\Delta\lambda_{\min}$ is varied between 1.0 [pu] to 1.85 [pu] in order to plot part of the pareto-optimal set. This pareto-optimal set can provide system operators and planners essential information relating power transfer levels and their associated voltage collapse margins. It can also provide a quick estimation of voltage collapse margins when dispatching different levels of power transactions especially for online purposes. From Figure 7, it is distinctive that power transfer capability and the voltage collapse margins are two conflicting objectives, and therefore an optimistic high power transfer level can sometimes compromises system stability. The proposed concept will now be extended to study on a larger scale power system, e.g. IEEE 118-bus system.

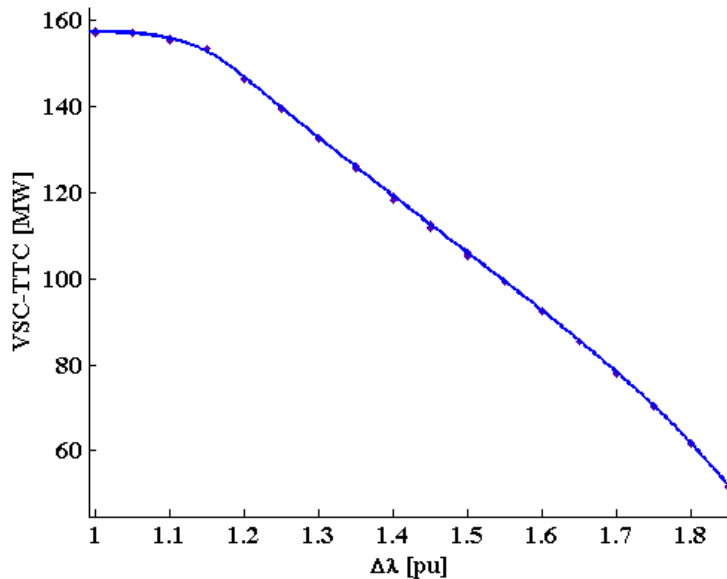


Figure 7. Approximated pareto-optimal front of VSC-TTC problem (9-bus system)

5.2 IEEE 118-BUS SYSTEM

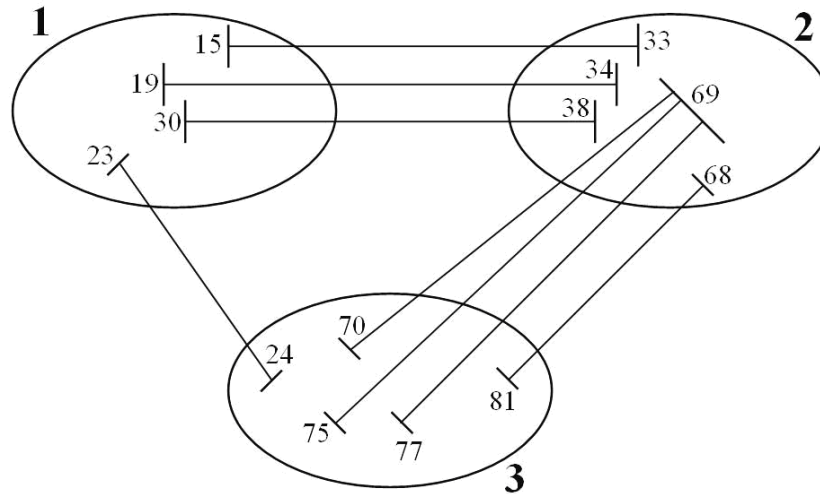


Figure 8. Interconnected areas of the IEEE 118-bus system

The IEEE 118-bus system from the Power Systems Test Case Archive UWEE webpage (2010) is considerably a large-scale test system, which consists of 54 generators and over 180 branches. To facilitate TTC studies, this system is divided into 3 areas with 8 tielines as shown in Figure 8. By solving the problem as shown by Equation (3), the distance to voltage collapse from the base case operating conditions is found to be $\Delta\lambda = 2.1871$ [pu].

5.2.1 TTC WITHOUT CONSIDERATION OF VOLTAGE STABILITY CONSTRAINTS

In this example, suppose the costs of electricity in Area 2 is the cheapest of all, then obviously, the objective is to determine the maximum power that can be exported out of Area 2 (see Figure 8). The resultant TTC problem can be expressed as follows:

$$\max \text{ fitness} = \sum_{i \in A2, j \notin A2} P_{ij} \quad (17)$$

where P_{ij} is the active power flow across tieline connecting bus i and j ; i and j are the sending buses in Area 2 (A2) and receiving buses in other areas

respectively. From 50 PSO trials, the best TTC found is 1965.85 [MW] as shown in Table 5.

	Best	Worst	μ	σ
TTC [MW]	1965.85	1755.44	1895.83	60.45

Table 5. Statistics of OPF-TTC (50 trials)

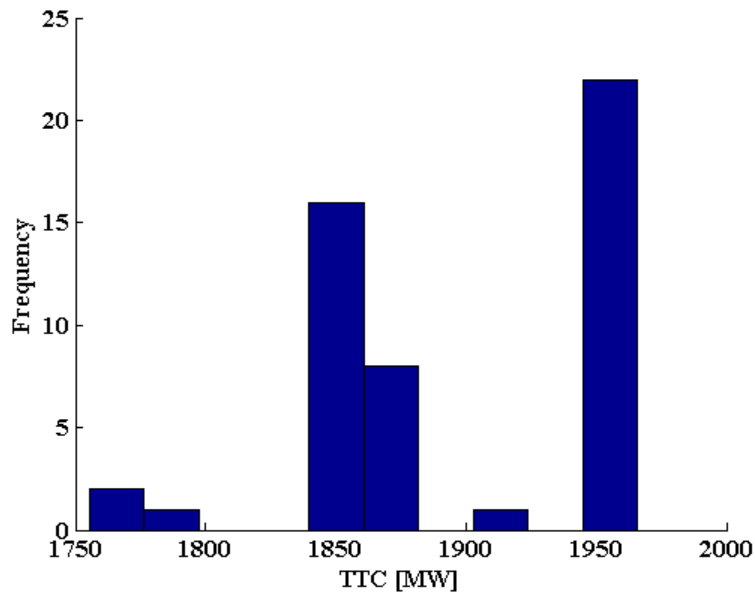


Figure 9. Histogram of TTC values [MW] (IEEE 118-bus system)

Figure 9 depicts the histogram from the statistics obtained from the PSO trials. Observe that for a large-scale problem dimension coupled with highly-nonlinear constraint equations considered, the performances of PSO deteriorated slightly over the 50 trials. Nevertheless, solution quality can be enhanced by increasing the population size and/or the maximum allowable generations depending on the given computational budget.

Having a maximal power of 1965.85 [MW] exporting out of Area 2 has resulted in a largely-reduced voltage collapse margin. Under this maximal transfer conditions, a number of generators' active and reactive power limits, and bus voltages limits are binding, and thus the voltage collapse margin $\Delta\lambda$ decreases significantly from a base case value of 2.1871 [pu] to 0.9218 [pu]. This is risky as any unexpected contingency event may cause the entire system to experience severe voltage instability issues, which may ultimately cause the system to collapse.

5.2.2 TTC CONSIDERING VOLTAGE STABILITY CONSTRAINTS

To operate the system slightly more conservatively, a voltage stability constraint of $\Delta\lambda \geq 1.25$ [pu] is now being imposed into the OPF-TTC model. Table 6 depicts the statistical results of VSC-TTC [MW]. The VSC-TTC is a mathematically-complex problem for such a large-scale system, however PSO can still provides important information, e.g. a histogram plot, can be extracted from these trials, which can indicate a range of secure VSC-TTC levels.

	Best	Worst	μ	σ
VSC-TTC [MW]	1666.72	1613.33	1628.66	11.99

Table 6. Statistics of VSC-TTC (50 trials, $\Delta\lambda \geq 1.25$ [pu])

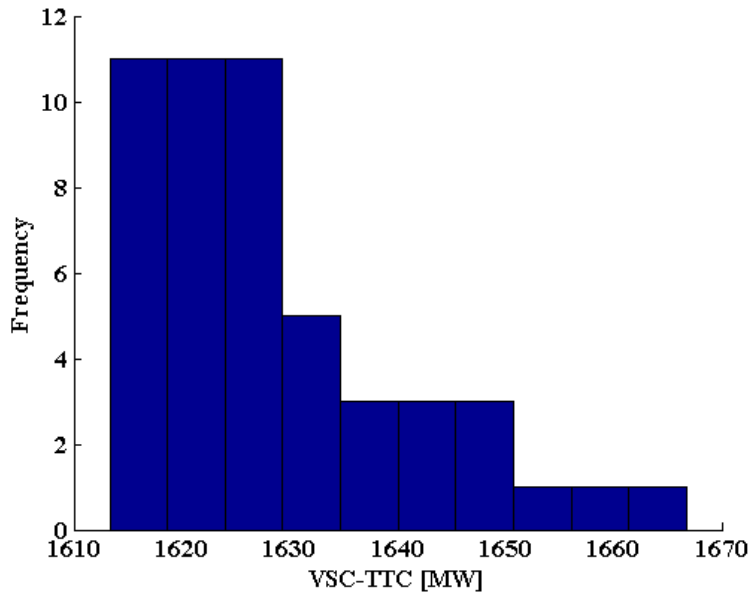


Figure 10. Histogram of VSC-TTC [MW] with $\Delta\lambda \geq 1.25$ [pu] (IEEE 118-bus system)

Figure 10 plots the histogram of VSC-TTC when considering a voltage stability limit of $\Delta\lambda \geq 1.25$ [pu] from the 50 PSO trials. Figure 11 plots the P-V curves of selected weak buses of the system. By reducing Area 2 power export by 299.13 [MW], the voltage stability margin of the system increases by 0.3282 [pu].

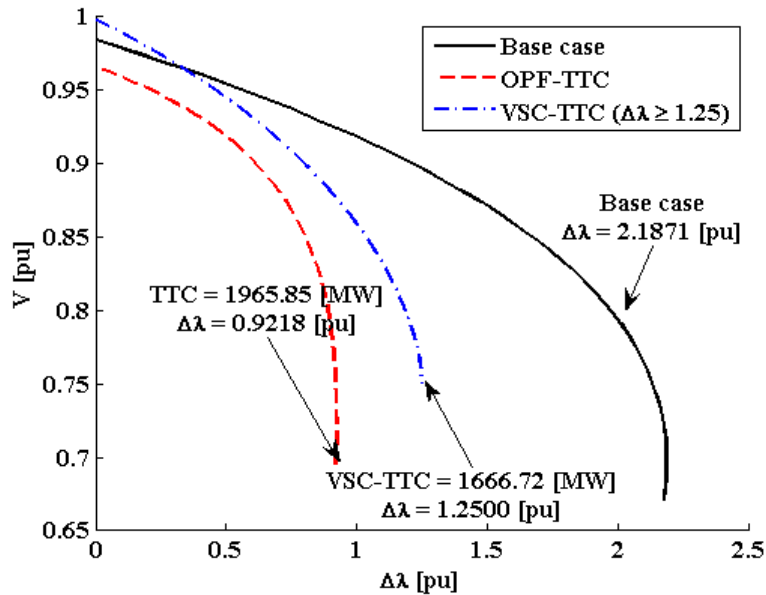


Figure 11. P-V curves of buses 44 and 81 (IEEE 118-bus system)

Similar to previous case study, the voltage stability margin $\Delta\lambda_{\min}$ is varied between 1.0 [pu] to 1.85 [pu], and Figure 12 estimates the pareto-optimal front relating TTC and $\Delta\lambda$. Notice that the pareto-optimal front of the IEEE 118-bus system case study exhibits highly-nonlinear relationships between power transfer capability and voltage collapse margins. Accuracies of the solutions lying on the pareto-optimal front can be enhanced by the following means: (i) increasing numbers of particles and/or generations and/or trials; (ii) improving the exploration and exploitation capabilities of PSO; and (iii) employing an advanced PSO technique, e.g. (Liu et al. 2007), to locate actual pareto-optimal sets etc.

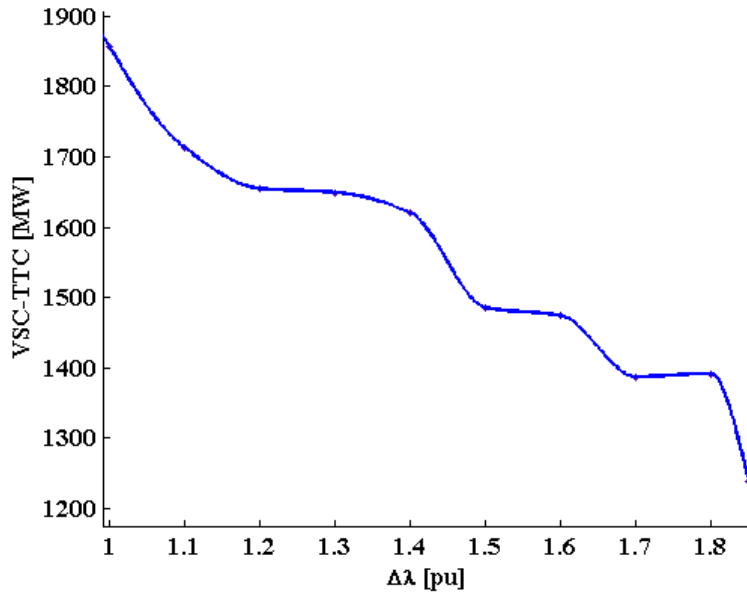


Figure 12. Approximated pareto-optimal front of VSC-TTC problem (IEEE 118-bus system)

As costs of electricity in Area 2 is assumed here to be the cheapest, limiting Area 2 export will naturally increase the overall costs of electricity of the system. This increment in costs can be regarded as the costs of the additional voltage stability margin [14]:

$$COST_{\Delta\lambda} = |COST_i - COST_j| \quad [\$ / hr] \quad (18)$$

where $COST_{\Delta\lambda}$ is the cost of additional voltage stability margin; $COST_i$ and $COST_j$ are the total costs of electricity of the entire system before and after the reduction of Area 2 power export respectively.

6. CONCLUSIONS

High power transfer levels across interconnected power networks due to economic reasons usually compromise system stability issues, i.e. forcing the systems to operate near the stability boundaries. This is undesirable as the unexpected losses of system components in critical locations could result in a catastrophic voltage collapse, and thus voltage stability issues must be considered during power transfer capability assessment. This paper presents a multi-objective Optimal Power Flow (OPF) problem, which is capable of evaluating

power transfer capability and its associated voltage stability margins. A Particle Swarm Optimization (PSO) algorithm is preferred over traditional optimization methods due to its robustness in handling non-differentiable or sometimes nonconvex objectives and complicated solution spaces. From the PSO trials, important pareto-optimal front information can be obtained, which reveals the unique and nonlinear relationships between power transfer capability and voltage collapse margins. Such information can be useful for online power transactions and transmission expansion planning with regards to system voltage stability margins. Advanced PSO techniques may be necessary to improve the accuracies of the pareto-optimal sets.

Given the ability of Evolutionary Computation (EC) techniques, such as PSO, to handle mix-integer programming problems, another possible future work can be directed to include the optimum control of transformer taps, shunt and series reactive power compensation devices etc, when evaluating voltage stability constrained power transfer capability.

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