Voltage Stability Constrained Optimal Power Flow (VSCOPF) with Two Sets of Variables (TSV) for Reactive Power Planning

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***Abstract*— The key of reactive power planning (RPP), or Var planning, is the optimal allocation of reactive power sources considering location and size. First, the relationships of Var compensation, total transfer capability (TTC), and fuel cost are introduced in this paper. Second, the enumeration approach for RPP is briefly described. Although time-consuming, it provides a global view of the relationship between the system cost and local Var compensation, which is useful for benchmarking purposes. Third, the voltage stability constrained optimal power flow (VSCOPF) model with two sets of variables (TSV) approach is used to combine a large number of OPFs in the enumeration approach to achieve an efficient model. The two sets of variables correspond to the normal operating point and the collapse point, respectively. The computational complexity of TSV is tremendously reduced. Different from the previous work using Var cost minimization as the objective, this work proposes to use the total system cost (fuel cost and Var cost) minimization as the objective. This leads to significantly different results. The observed results have important implication to RPP, especially under the deregulated environment. That is, it verifies that RPP should consider the impact to system dispatch considering generation cost. The results from the TSV approach are also benchmarked with the enumeration approach. Finally, conclusions are presented.**

***Index Terms*— Voltage stability constrained optimal power flow (VSCOPF), reactive power planning (RPP), Var planning, total transfer capability (TTC), stability margin (SM), two sets of variables (TSV).**

I. INTRODUCTION

REACTIVE power has been a critical issue in power system planning and operation, as evidenced by the Great Northeast Blackout in August 2003. Also, the power industry has been under pressure to serve load economically since deregulation was initiated in the early 1990's. Therefore, the planning of Var resources, or reactive power planning (RPP) should be considered in a competitive environment while meeting the required security standard.

Reference [1] demonstrates a technically viable approach to quantitatively assess the benefits from Var sources at the demand side, under the competitive environment. On one hand, injection of reactive power at the receiving end reduces the reactive power through transmission lines and therefore reduces the line current, thus the real power loss (I^2R) will be reduced. Also, this will reduce reactive power flow to allow more real power flow if the same MVA capacity is assumed. On the other hand, shunt reactive power compensation can reduce the chance of voltage collapse by increasing the maximum transfer capability or the load level at the point of collapse (PoC), as shown by the three PV curves in Fig. 1. It should be noted that a security margin (SM) is typically enforced to ensure that the system is operated with a safe distance from voltage collapse. As shown in Fig. 1, SM is measured by the load distance between the operating point, A, and the PoC point, B.

The benefit analysis in [1, 6] shows the nonlinear relationship among the Var compensation, TTC limit, and fuel cost variation, as shown in Fig. 2. Typically, an optimal power flow (OPF) run is needed to obtain the updated TTC limit after the Var compensator is connected, and another OPF run is needed to obtain the new fuel cost for generation dispatch considering the updated TTC limit. This two-OPF combination can be repeated to find the economic benefits for many different locations and different sizes of Var compensators. This is essentially the enumeration approach for RPP, as described in Section II.

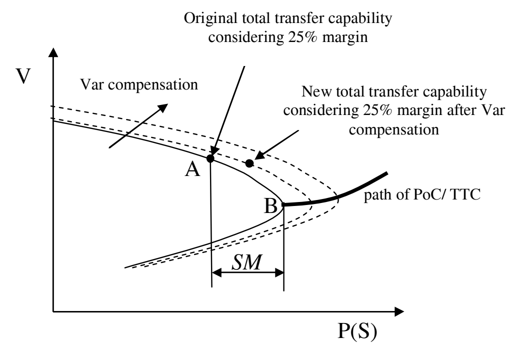

Fig. 1. Original and new TTCs considering security margin.

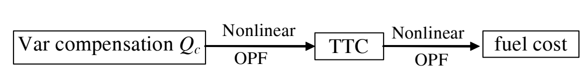

Fig. 2. Relationships of fuel cost, TTC and Var compensation

However, a more efficient approach is highly desirable to solve RPP with the consideration of voltage stability constraint. This has been an essential issue when the location

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and size of new Var sources need to be determined during RPP. References [2] and [3] have incorporated the static voltage stability margin in RPP, which provide more realistic solutions. More recent research regarding RPP considering voltage stability limit can be found in an informative literature review [4], which summarizes three important components in RPP: the objective functions, the constraints, and the mathematical algorithms. In addition, more details of rigorous mathematical algorithms can be also found in [5].

This paper will present an enhanced version of two sets of variables (TSV) approach to solve VSCOPF for RPP. Different from the previous works [2-3] that use Var cost minimization as the objective function, this work proposes to use the total cost (fuel cost and Var cost) minimization as the objective. Although this is a small change mathematically, it leads to significantly different results. The observed results have important implication to RPP, especially under the deregulated environment. That is, the impact from Var compensation to system dispatch regarding generation cost is significant enough to be considered. In addition, the results from the enhanced TSV approach are also benchmarked with the enumeration approach.

This paper is organized as follows. Section II illustrates the enumeration approach. Section III presents the enhanced TSV approach for the VSCOPF model. Section IV presents the test results from a seven-bus system with Var compensation, and Section V presents the conclusion.

II. Enumeration Approach

The study on RPP presented in this section will consider the updated tie line total transfer capability (TTC) limit due to Var compensation. To avoid confusion, here the Base Case and Compensated Case are defined. The Base Case is referred to as the base system without Var compensation; and the Compensated Case is referred to as the case with Var compensators available at a given bus in a given amount and the original tie-line transfer capability limit is updated by a new limit.

Considering the nonlinear relationships among the fuel cost variation, TTC limit, and Var compensation, a straightforward enumeration approach is proposed below.

1. An OPF for generation dispatch is performed to find the minimal total system cost for the Base Case.
2. For a given location and a given size, use TTC OPF model to obtain the updated TTC limit for this compensated case, and then use another OPF for generation dispatch for cost minimization with the updated TTC limit. This two-OPF-combination run can be repeated with two loops, one for different locations and the other for different Var sizes.
3. The base case cost will be compared with each compensated case to obtain the cost reduction after Var compensation. It should be noted that this cost reduction considers the Var impact to TTC limit.

The objective of the second OPF run is to minimize the total cost (the fuel cost and the Var cost). The constraints include the limits of the transmission network. The formulation of the OPF model can be written as follows:

$$\text{Min: } \sum f(P_{Gi}) + Var\,cost$$

Subject to:

$$P_{Gi} - P_{Li} - P(V,\theta) = 0 \quad (\textit{Real power balance})$$

$$Q_{Gi} + Q_{ci} - Q_{Li} - Q(V,\theta) = 0 \quad (\textit{Reactive power balance})$$

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \quad (\textit{Generation real power limits})$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad (\textit{Generation reactive power limits})$$

$$V_i^{\min} \le V_i \le V_i^{\max} \quad (\textit{Voltage limits})$$

$$Q_{ci}^{\min} \le Q_{ci} \le Q_{ci}^{\max} \quad (\textit{Compensation limits})$$

$$\left|LF_l\right| \le LF_l^{\max} \quad (\textit{Line flow thermal limits})$$

$$\sum_{l \in Lt} S_l \le \sum_{l \in Lt} S_l^{\max} \quad (\textit{Tie line MVA transfer capability limits})$$

where

$i \in$ the set of buses; $l \in$ the set of lines; f — fuel cost function; $Lt \in$ the set of tie lines; P_{Gi} — generator active power output; P_{Li} — load active power; Q_{Li} — load reactive power; Q_{Gi} — generator reactive power output; V_i — bus voltage; Q_{ci} — Var source installed at bus i; S_l — tie-line MVA flow; LF_l — transmission line flow.

Assuming Z_B and Z_C are the total cost for the Base Case and a Compensated Case, we have the total cost reduction after Var compensation given by $\Delta c = Z_B - Z_C$. The relationship between Δc and Q_c at a specified location and amount can be built as shown in Fig. 3. Thus, the optimal location can be achieved by identifying the maximum total cost reduction in Δc-Q_c curves at all candidate buses as illustrated in Fig. 3.

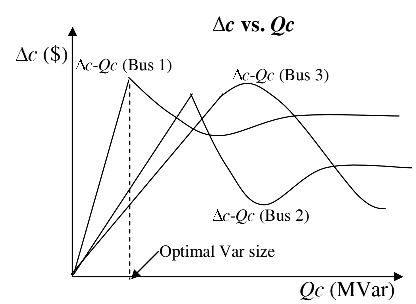

Fig. 3. Identify the optimal location and Var size from Δc versus Q_c curves.

Although this approach is time-consuming, it does give a full spectrum and insightful information about the total cost reduction if a Var compensator is installed at a specific location in various amounts. This approach may be used for benchmarking purposes, as done in this paper.

III. VSCOPF Model with Two Sets of Variables (TSV)

A. General Format of VSCOPF Model with TSV

In the previous section, TTC OPF model and generation dispatch OPF are performed for many Compensated Cases (*1+2mn* times). Here, n is the number of possible Var size at each location, m is the number of candidate locations, and *1* stands for the very initial generation dispatch OPF. These *1+2mn* OPF runs are computationally intensive. Therefore, it will be a great achievement if all the models can be combined in one optimization model to minimize the total cost. A voltage stability constrained OPF (VSCOPF) model with the two sets of variables (TSV) approach to update the TTC limit and to minimize total cost simultaneously in one optimization model is introduced here.

Reference [7] summarized a generic TSV formulation as a mathematical model to handle the voltage stability issue. However, it does not address the application of TSV approach in RPP. Other works in [2-3] use a similar TSV approach to model constraints for RPP with Var cost minimization as the objective function. This cost model is reasonable for regulated power industry, but not for de-regulated industry. The reason is that if the value or benefit from Var compensation is ignored, the motivation to install a Var compensator is much weakened from the viewpoint of system operators and planners, as demonstrated by the following discussions and test results.

This paper employs a new objective function that is to minimize the sum of fuel cost and Var cost, which represents the true optimization model of RPP in a competitive environment. The results show that the new objective function may lead to a significant difference in the choice of optimal Var location and size.

The goal here is to build a model to find out the optimal Var location and size that minimize both fuel cost and Var cost, while simultaneously considering the increased system voltage stability limit. The challenge is that voltage stability limit, nonlinearly related to the Var location and size, is unknown before the optimization is solved. This will be addressed by the TSV model discussed below.

It is common that voltage stability is ensured by forcing the operating point away from the PoC (or critical point) at least a pre-defined distance measured by MVA percentage. For this reason, two sets of network variables and power flow constraints corresponding to the "normal operating point" and "critical point or PoC" are adopted here for the RPP planning model. A generic format of VSCOPF model with TSV is as follows:

Min: $C(x_o, \rho)$

Subject to:

$$F(x_o, \rho, TTC_o) = 0$$
$$F(x_*, \rho, TTC_*) = 0$$
$$(TTC_* - TTC_o)/TTC_* = SM$$
$$SM \geq SM_{spec}$$
$$x_{o,min} \leq x_o \leq x_{o,max}$$
$$x_{*,min} \leq x_* \leq x_{*,max}$$
$$\rho_{min} \leq \rho \leq \rho_{max}$$

where "o" stands for the "normal operating point" A in Fig. 1 and "*" for the "critical point or PoC" B in Fig. 1; x represents dependent system variables such as voltage V, angle Θ, generator real power and reactive power output P_G and Q_G, whose upper bounds and lower bounds are applicable to both the normal operating point and the critical point as $x_{o,max}$, $x_{o,min}$, $x_{*,max}$, $x_{*,min}$ respectively; ρ represents power system independent parameters and control variables such as Var compensation Q_c, which are the same in both "normal operating point" and the "critical point"; TTC represents tie line total transfer capability; $C(x_o, \rho)$ represents the operating cost and the Var cost function that usually depends on some of the system variables such as P_G at the current operating point and control variables such as Q_c; $F(x, \rho, TTC) = 0$ represents steady-state power flow equations of the system, which are valid to both of the normal operating point and PoC. The voltage stability margin SM is the connection between the two sets of variables.

B. Detailed VSCOPF Model with TSV

The above generic VSCOPF format will be expanded to a detailed model especially for RPP in this subsection as follows:

Min: $\sum f_1(P_{Goi}) + \sum f_2(Q_{ci}) \times y_i$

Subject to:

(1) The following constraints are applicable to both of the normal operating point and PoC:

$$\sum y_i = k \quad \textit{(Number of Var compensator installations)}$$
$$P_{Goi} - P_{Loi} - P(V_o, \theta_o) = 0 \quad \textit{(Real power balance)}$$
$$P_{G*i} - P_{L*i} - P(V_*, \theta_*) = 0$$
$$Q_{Goi} + Q_{ci} - Q_{Loi} - Q(V_o, \theta_o) = 0 \quad \textit{(Reactive power balance)}$$
$$Q_{G*i} + Q_{ci} - Q_{L*i} - Q(V_*, \theta_*) = 0$$
$$P_{Gi}^{\min} \leq P_{Goi} \leq P_{Gi}^{\max} \quad \textit{(Generation real power limits)}$$
$$P_{Gi}^{\min} \leq P_{G*i} \leq P_{Gi}^{\max}$$
$$Q_{Gi}^{\min} \leq Q_{Goi} \leq Q_{Gi}^{\max} \quad \textit{(Generation reactive power limits)}$$
$$Q_{Gi}^{\min} \leq Q_{G*i} \leq Q_{Gi}^{\max}$$
$$V_i^{\min} \leq V_{oi} \leq V_i^{\max} \quad \textit{(Voltage limits)}$$
$$V_i^{\min} \leq V_{*i} \leq V_i^{\max}$$
$$|LF_{lo}| \leq LF^{\max} \quad \textit{(Line flow thermal limits)}$$
$$|LF_{l*}| \leq LF^{\max}$$
$$SM = \frac{\sum_{l \in Lt} S_{l*} - \sum_{l \in Lt} S_{lo}}{\sum_{l \in Lt} S_{l*}} \quad \textit{(Tie line MVA TTC security margin)}$$
$$SM \geq SM_{spect} \quad \textit{(Security margin limits)}$$
$$Q_{ci}^{\min} \leq Q_{ci} \leq Q_{ci}^{\max} \quad \textit{(Compensation limits)}$$

(2) The following constraints are only applicable to PoC:

$$P_{L*i} \geq P_{L*i}^0 \ (i \in Sink) \quad \textit{(real load in load center increases)}$$
$$Q_{L*i} \geq Q_{L*i}^0 \ (i \in Sink) \quad \textit{(reactive load in load center increases)}$$
$$P_{G*i} \geq P_{G*i}^0 \ (i \in Source) \quad \textit{(real power generation in generation center increases)}$$
$$P_{G*i} = P_{G*i}^0 + \frac{\left(\sum_{i \in Source} P_{G*i} - \sum_{i \in Source} P_{G*i}^0\right) \times \left(P_{Gi}^{\max} - P_{G*i}^0\right)}{\sum_{i \in Source}\left(P_{Gi}^{\max} - P_{G*i}^0\right)} \quad \textit{(pattern of generation increase)}$$

$$P_{L*i} = P_{L*i}^0 + \frac{\left(\sum_{i\in Sink} P_{L*i} - \sum_{i\in Sink} P_{L*i}^0\right)\times P_{L*i}^0}{\sum_{i\in Sink} P_{L*i}^0} \quad \textit{(pattern of load increase)}$$

$$P_{L*i} / P_{L*i}^0 = Q_{L*i} / Q_{L*i}^0 \quad \textit{(maintaining constant power factor when load increases)}$$

where
o — normal operating point;
$_*$ — critical point (PoC);
k — number of Var compensator installations;
$f_1(P_{Goi})$ — fuel cost for generator at bus i;
$f_2(Q_{ci})$— Var cost at bus i;
y_i —binary variable, y_i = 1 if the bus i is selected for Var installation; otherwise 0;
$P_{L*i}{}^0$, $Q_{L*i}{}^0$, $P_{G*i}{}^0$— initial values for the PoC case.

The x variable of the generic VSCOPF format corresponds to {V, θ, P_G, Q_G, P_{L*}, Q_{L*}} in the detailed VSCOPF model; ρ includes independent parameters {P_{Lo}, Q_{Lo}, k, SM_{spec}, $P_{L*i}{}^0$, $Q_{L*i}{}^0$, $P_{G*i}{}^0$, all upper bounds, and all lower bounds}, and control variables {Q_c, y}.

By using this model, TTC_* can be automatically pushed to the maximum transfer capability without running another TTC OPF as what is done in the enumeration approach. Here, an implicit assumption is that the tie-line power always flows from a generation center (lower fuel cost) to a load center (higher fuel cost), which is reasonable since Var compensators are usually installed in load centers to increase voltage stability constrained transfer limit. Because minimizing fuel cost leads to transferring cheaper power from the generation center to the load center as much as possible, thus the tie-line transfer capability for the normal operating point, TTC_o, will be pushed as high as possible. As a result, tie line transfer capability for the critical point, TTC_*, will also be pushed as far as possible on the P-V curve to satisfy the pre-defined security margin. This essentially ensures that the final solution is optimal while being subject to the required security margin.

However, if the objective function does not include minimizing fuel cost, TTC_o and TTC_* will not be pushed as far as possible on the P-V curve, since the motivation to increase TTC and then to decrease fuel cost does not exist. The case study will show this in details.

IV. Case Study and Results

A. Test System

In this section the seven-bus test system from PowerWorld is used to demonstrate the optimal location and size selection for Var compensation. The diagram of the test system is shown in Fig. 4. The data for the loads, generators, transmission thermal limits, and voltage limits are shown in Table I. The test system is divided into two areas, the Load Center (LC) in the top and the Generation Center (GC) in the bottom, as shown in Fig. 4 and Table II. The generators in the LC are more expensive than those in the GC. The tie line interface consists of Lines 6-2 and 7-5.

The OPF models in this paper are programmed in General Algebraic Modeling System (GAMS), and are solved by the Nonlinear Programming (NLP) solver MINOS and Mixed Integer Nonlinear Progra P) solver SBB.

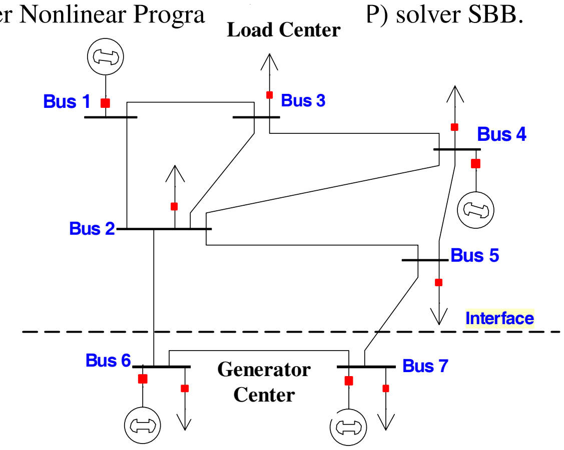

Fig. 4. Diagram of a seven-bus test system.

Table I. Parameters of the test system

Power base: 100MVA

Voltage base: 138kV

Load

Bus	1	2	3	4	5	6	7
P_L (MW)	0	100	190	150	200	50	80
Q_L (MVar)	0	40	75	50	60	20	40

Generator fuel consumption cost (=a+b×P_G)

Bus	1	4	6	7
a ($/hr)	798.92	814.03	515.34	400.41
b ($/MW*hr)	20	19	14	15
Marginal Cost ($/MW*hr)	20	19	14	15

Active power generation limits (MW)

Bus	1	4	6	7
$P_G{}^{max}$	150	200	300	300
$P_G{}^{min}$	70	50	60	0

Reactive power generation limits (MW)

Bus	1	4	6	7
$Q_G{}^{max}$	100	100	100	100
$Q_G{}^{min}$	-100	-100	-100	-100

Transmission line thermal limits (MVA)

Line	1-2	1-3	2-3	2-4	2-5	4-3	5-4	6-2	6-7	7-5
Limit	120	100	100	100	100	120	80	250	100	250

Voltage limits (p.u.)

V_{max} =1.05 and V_{min}=0.95 for every bus.

Table II. Load and Generations in Two Areas

Area	Bus	Gen. Cap. (MW)	Load (MW)	Margin (MW)
Load Center	1, 2, 3, 4, 5	350	640	-290
Gen. Center	6, 7	600	130	470

B. Results from the Enumeration Approach

Assume Bus 2, Bus 3, and Bus 5 are three Var compensation location candidates. The TTC OPF model becomes infeasible if Q_c is greater than about 200 MVar, so the upper limit of Q_c size in this case is set to 200 MVar. If 1 MVar step change is chosen, 200 evaluations (or 400 OPF runs) need to be performed for each bus.

By applying the procedure in Section II, Fig. 5 provides the whole picture for the total cost (fuel cost + Var cost) reduction tendency with Var compensation increase at Bus 2, Bus 3, and Bus 5, respectively. The economic efficiency of Var compensation may not continuously grow as the Var compensation amount grows.

As Fig. 5 shows, Δc_bus2, Δc_bus3 and Δc_bus5 rapidly increase from 0 and then reach their maximum values \$46.46/hr, \$88.94/hr and \$53.86/hr, when Q_c_bus2 = 34 MVar, Q_c_bus3 = 15 MVar, and Q_c_bus5 = 35 MVar, respectively. Then, these curves start to decline. The criterion of location and size selection is based on maximum total cost (fuel cost and Var cost) reduction. It is apparent that installation of 15 MVar Q_c at Bus 3 is the best choice. It should be noted that when the Var size is beyond 62 MVar, Var compensation at any of the three buses becomes non-economic since Δc drops below zero.

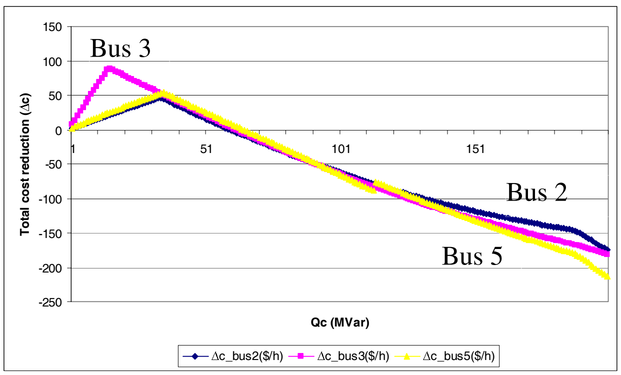

Fig. 5. Total cost reduction compared with Base Case at candidate buses versus Var compensation.

C. Results from VSCOPF Model with the Two Sets of Variables (TSV) Approach

The results of variables at the "present operating point (o)" and the "critical point ($*$)" are shown in Table III. The tie line TTC limit, TTC_o, is 369.54 MVA if a 25% security margin is enforced to keep the operating point away from the collapse point, TTC_*, at 492.73MVA. The optimal solution for RPP with TSV approach is to install a Var compensator of 14.54 MVar at Bus 3. The answer is very close to but should be more accurate than the enumeration approach result – 15 MVar at Bus 3, since Q_c variable is treated as a continuous one in TSV instead of integer variable in the enumeration approach.

It is worthwhile to analyze the difference of this work and the previous works in [2-3]. From here and forward, the TSV model in the previous works [2-3] is named TSV Model I, and the TSV model in this paper is named TSV Model II for convenient illustration. The objective for the proposed TSV Model II is minimizing the sum of fuel cost and Var cost, but TSV Model I treats minimizing Var cost as the only objective, i.e., $\min \sum f_2(Q_{ci}) \times y_i$. Although the objective function is slightly different, the results are significantly different.

Table IV shows the detailed results comparison of the enumeration approach, TSV Model I, and TSV Model II. TSV models save much computational time if compared with the enumeration approach. The final result of enumeration is listed for comparison and benchmark purposes. Table IV also shows that the TSV Model I does not suggest any Var compensator installation since the Var cost is minimized to zero. However, the total transfer capability corresponding to the operating point (TTC_0) and the collapse point (TTC_*) are all lower than that of TSV Model II. This is because there is no motivation in TSV Model I to push the operating point and the PoC further right on the P-V curve. The optimal solution with Model I stops at an "operating point" with a stability margin (SM) greater than the required 25% margin as shown in Fig. 6. Table IV shows that the total cost from TSV Model I is \$322.42/hr higher than that in TSV Model II. Therefore, TSV Model II proposed in this paper can lead to significantly different results from and is a great improvement over TSV Model I in the previous works, which is more suitable for vertically regulated power industry, instead of competitive deregulated industry.

Table III. Results from VSCOPF model with the proposed TSV approach.

Objective							
Fuel cost (\$/hr)		Var cost (\$/hr)		Total cost (\$/hr)			
15168.98		24.46		15193.44			
Variables output							
Bus	1	2	3	4	5	6	7
Q_c (MVar)			14.54				
y (binary)			1				
P_{Go} (MW)	85			200		300	196
Q_{Go} (MVar)	81			100		52	55
P_{Lo}(MW)		100	190	150	200	50	80
Q_{Lo}(MVar)		40	75	50	60	20	40
V_o (V)	1.05	1.01	0.99	1.00	0.97	1.04	1.01
TTC_o(MVA)	369.54						
P_{G*} (MW)	70			200		300	300
Q_{G*} (MVar)	63			100		98	100
P_{L*}(MW)		113	215	170	226	50	80
Q_{L*}(MVar)		47	87	60	73	20	40
V_* (V)	1.02	1.00	0.95	0.97	0.97	1.05	1.03
TTC_*(MVA)	492.73						

Table IV. Results comparison of three models: Enumeration, TSV Model I, and TSV Model II.

	Enumeration approach	TSV model to minimize Var cost only (**TSV Model I**)	TSV model to minimize fuel cost + Var cost (**TSV Model II**)
Running time (s)	81	0.156	0.328
Fuel cost (\$/hr)	15169.13	15515.86	15168.98
Var cost (\$/hr)	25.21	0.00	24.46
Total cost (\$/hr)	15194.34	15515.86	15193.44
Var location	Bus 3	None	Bus 3
Var size (MVar)	15	0.00	14.54
TTC_o(MVA)	369.46	304.39	369.54
TTC_*(MVA)	492.61	464.28	492.73
SM	25%	34%	25%

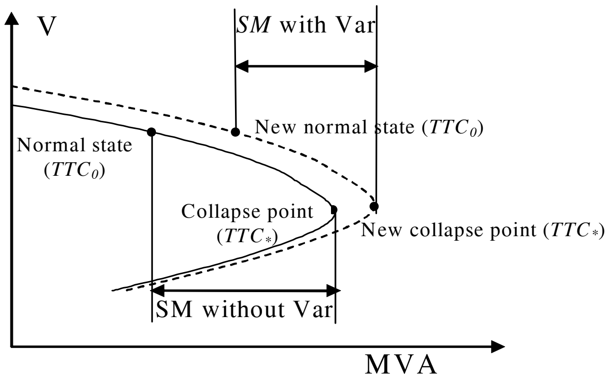

Fig. 6. Comparison of normal state operating point TTC_0 and the collapse point TTC_* of TSV Model I and TSV Model II.

V. Conclusions

This paper discusses reactive power planning (RPP) considering the voltage stability constraints. The enumeration approach and an improved version of the Two Sets of Variables (TSV) approach are discussed to solve the VSCOPF model for RPP. The following observations and conclusions can be drawn from this work:

- The economic efficiency of Var compensation may not grow as the Var compensation amount grows. It may be an economical loss if the Var size is beyond a certain range.
- Although the enumeration approach may need $1 + 2nm$ OPF runs in a two-step procedure for each possible location and size, it does give a full spectrum and insightful information about the fuel cost reduction if a Var compensator is installed at a specific location in various amounts. This approach may be used for benchmarking purpose.
- VSCOPF model with TSV combines Base Case, Compensated case, and TTC models in the enumeration approach into one model, therefore, the reactive power planning problem can be efficiently solved in only one step by automatically pushing TTC as high as possible subject to economical efficiency.
- The results show that the new objective function in the improved TSV model may lead to significantly different results from and is a great improvement over the TSV model in the literature. The improved TSV model is more suitable for the competitive power industry.
- The results from the enumeration approach and the improved TSV model are very close. This validates the TSV model.

VI. Acknowledgement

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VIII. Biographies

Wenjuan Zhang (S' 2003) received her Ph.D. degree from The University of Tennessee in 2007. She received the B.S.E.E. from Hebei University of Technology, China, in 1999 and the M.S.E.E. from Huazhong University of Science and Technology, China, in 2003. She is presently working at the California Independent System Operator (CAISO). Her current interests include reactive power compensation and planning, voltage stability, and power system optimization.

Fangxing (Fran) Li (M' 2001, SM'2005) has been an Assistant Professor in the ECE Department at The University of Tennessee (UT), Knoxville, TN since August 2005. Prior to joining UT, he worked at ABB Inc., Raleigh, NC as a Senior Engineer and then a Principal Engineer. His current interests include reactive power, distributed generation, energy markets, reliability, computational methods, and power electronics. He received his Ph.D. degree from Virginia Tech in 2001. Dr. Li is a Registered Professional Engineer in the state of North Carolina.

Leon M. Tolbert (SM' 1999) received his B.S., M.S., and Ph.D. degrees all from Georgia Tech, Atlanta in 1989, 1991, and 1999, respectively. He joined the Engineering Division of Oak Ridge National Laboratory (ORNL) in 1991. He was appointed as an assistant professor in the ECE Department at The University of Tennessee in Knoxville in 1999. He is presently an Associate Professor at UT and a research engineer at ORNL. He is a Registered Professional Engineer in the state of Tennessee.