Controlling Reactive Power Flows in Boundary Transformers

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***Abstract*—This paper presents the results of a study of the different alternatives that System Operators use to address the reactive power flow control problem in transmission/subtransmission boundary transformers. The control problem is formulated and solved using a conventional OPF algorithm including additional constraints to keep reactive power flows between imposed limits. The problems arising from the inclusion of these new restrictions, along with the need to distinguish between networks operated by different agents (TSO, DSOs), are presented and discussed.**

Keywords- Power system operation; reactive power flows; OPF

I. INTRODUCTION

Voltage and reactive power control are usually classified as ancillary services [1-7], establishing reactive power requirements applicable to generators, transmission service providers and consumers. Most of deregulated power systems [8] also extend these issues to distribution network utilities, as they are considered to be large consumers connected to the bulk transmission network. This implies specific reactive power flow constraints for any transformer connecting a distribution network to the transmission network (boundary transformers). In this way, NERC establishes these specific rules as a set of recommendations [9], and, in a recent study [10], CIGRE also underscores the importance of reaching similar objectives in the management of reactive power in power systems.

In this new paradigm, System Operators, either transmission or distribution, must control transmission and subtransmission networks in terms of reactive power flows in boundary transformers, taking into account the new constraints imposed. This paper is focused on how the SOs (TSOs and DSOs) address the problem of controlling reactive power flows in boundary transformers.

II. PROPOSED APPROACH

Figure 1 shows a schematic diagram of a typical power system. There are two areas, well distinguished according to theirs voltage levels: transmission and subtransmission. Both systems are connected by transformers which make up the border (boundary transformers). Each area has different controls to operate the corresponding network.

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The control of the reactive power flow in boundary transformers can be formulated as an OPF problem, where limitations on such reactive power flows are incorporated as a new constraint. The solution provides optimal values for control variables that ensure that all technical and operational constrains are satisfied, and that an objective function is minimized.

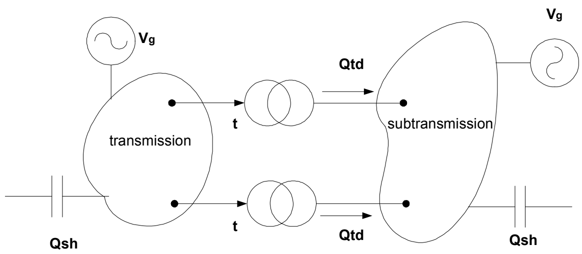

Figure 1. Schematic diagram of a typical T/S power system.

III. OPF FORMULATION

Assuming that the active power generation has been scheduled according to electric market rules, it is possible to minimize network power losses by properly adjusting, within permissible limits, the control parameters at the System Operator's disposal, that is, generator voltage magnitudes, transformer taps and switchable VAR sources. In this process, constraints on certain dependent variables, i.e., bus voltages, generator reactive powers and, particularly, reactive power flows in transmission-subtransmission boundary transformers, should be enforced as well.

The following optimization problem is proposed:

$$\begin{aligned}
&\min f(X) \\
&s.a. \\
&\qquad h(X) = 0 \\
&\qquad d(X) = 0 \\
&\qquad V^{\min} \le V \le V^{\max} \\
&\qquad T^{\min} \le T \le T^{\max} \\
&\qquad Q^{\min} \le Q \le Q^{\max} \\
&\qquad 0 \le S^2 \le S^{\max} \\
&\qquad K^{\min} \le TAN \le K^{\max}
\end{aligned} \tag{1}$$

where:

$X = [\theta, V, T, Q, P_{ij}, Q_{ij}, S^2, TAN]^t$: Variables

$f(X)$: Active power losses (Objective function)

$h(X)$: Network equations

$d(X)$: Inequality constraints

V: Voltages

T: OLTC taps

Q: Reactive power injections

S^2: Tie-lines apparent power flow

$TAN\phi$: Q/P ratio in boundary transformers

The last constraint, $K^{\min} \leq TAN\phi \leq K^{\max}$, is imposed in transmission-subtransmission boundary transformers. Usually, the limits on the reactive power flow are established in form of power factor or as a percentage of the active power flow in the transformer. However, the formulation of this constraint in terms of the ratio $\tan\phi = Q_{flow} / P_{flow}$ in each boundary transformer simplifies the OPF problem formulation and its solution, avoiding the use of binary variables.

IV. TEST CASES

The presented cases in Figure 2 have been analyzed:

Case 1: Classical loss optimization, without reactive power flow constraints, on the whole system.

Case 2: Transmission network optimization without considering subtransmission networks. The subtransmission network is replaced by a set of loads at each boundary bus, P_L being the active power flow at the boundary transformer in the base-case, and Q_L alternatively set as follows:

Case 2_1: $Q_L = 0.33 P_L$. This value of Q_L is the upper limit of the permitted reactive power flow, i.e., the worst case regarding reactive power flows. The transmission system should supply part of the reactive power consumed by subtransmission networks.

Case 2_2: $Q_L = 0$. This value of Q_L is the lower limit of the permitted reactive power flow, i.e., the most favourable case regarding reactive power flows. The transmission network does not provide or demand reactive power.

Case 3: Only the losses of the subtransmission network are minimized, using controls located in this network, i.e., under the control of the DSO. Controls located in the transmission network are fixed to the values obtained in Case 2_1 or Case 2_2. Two alternatives are analysed:

Case 3_1: No reactive power flow constraints on boundary transformers are considered.

Case 3_2: Reactive power flow constraints are imposed on the OPF.

Case 4: Loss minimisation of the whole system including reactive power flow constraints in transmission/subtransmission transformers.

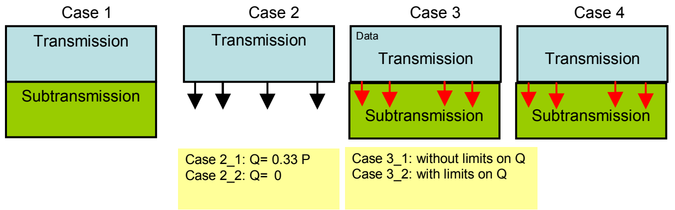

Figure 2. Test cases.

V. RESULTS

This section presents the results obtained in the IEEE RTS-96 24 bus-network. This network has two voltage levels with 5 boundary transformers. The transmission level (230 kV) includes 8 generators as control variables, and the subtransmission level (138 kV) includes 3 generators, 5 OLTC (the boundary transformers) and a reactor as control variables (Figure. 3).

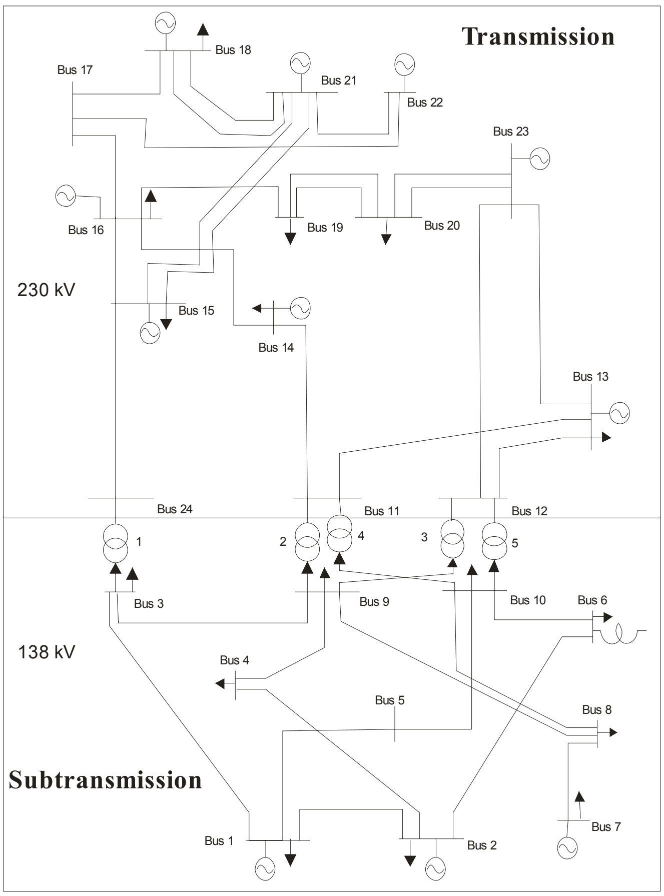

Figure 3. IEEE 24-bus network including two control areas.

The base case scenario was generated as in [11]. A winter weekday (week 51, Tuesday) and flat-hour scenario has been considered.

First, a comparison between cases 1 and 4 will be presented. In these cases the whole system optimization is performed, respectively excluding and including reactive power flow constraints. Then, the results of performing partial optimizations (i.e., separately optimizing the transmission and distribution networks) will be presented.

A. Case 1 vs Case 4

First, the active power losses (objective function) will be compared (Table I). Obviously, Case 1 is the optimal regarding the losses as the whole system is optimized without reactive power flow constraints. Besides, Case 4 provides better losses than the Base Case but more than Case 1. This is due to Case 4 being more constrained than Case 1.

Table I. Active power losses of the whole system (p.u.).

	Ploss	% improvement
Base case	0.4651	-----
Case 1	0.4229	9.08
Case 4	0.4510	3.02

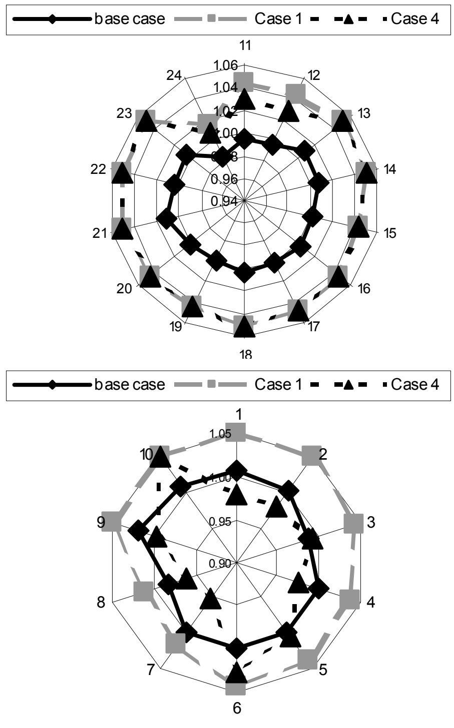

Figure 4. a) Transmission bus voltages; b) Subtransmission bus voltages.

One interesting result is the voltage profile obtained with the different OPF formulations (Figure 4). Voltage limits are set to 1.05 and 0.95 p.u. respectively. Note that voltages are kept within limits, and that, in both cases, transmission voltages are raised in order to reduce losses. Note, however, that subtrasmission voltages can only be raised if no reactive power flow constraints are included (Case 1). In Case 4, voltages are even reduced in order to meet the additional constraints. In fact, it is necessary to allow significant reactive power flows between transmission and subtransmission networks to make it possible to obtain an adequate voltage profile on the lower voltage level.

From the point of view of system operation, it is interesting to compare the required control actions provided by both OPF problems in order to minimize system losses. Figure 5 presents the generator voltage set-points. Note that subtransmission generators (1, 2 and 7) would have a difference behavior in both solutions, while the transmission ones behave quite similarly. However, the control variables responsible for the reorganization of reactive power flows between both subnetworks are the transformers taps. This fact is shown in Figure 6.

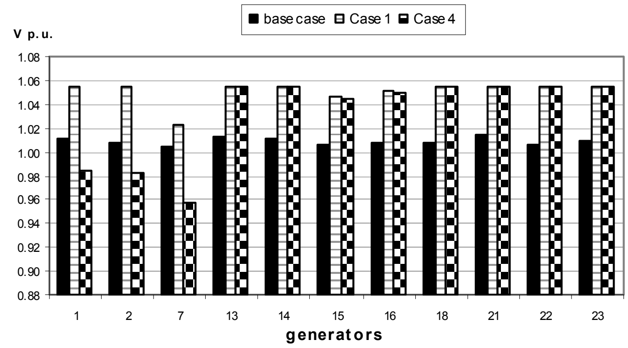

Figure 5. Voltage set-points of generators.

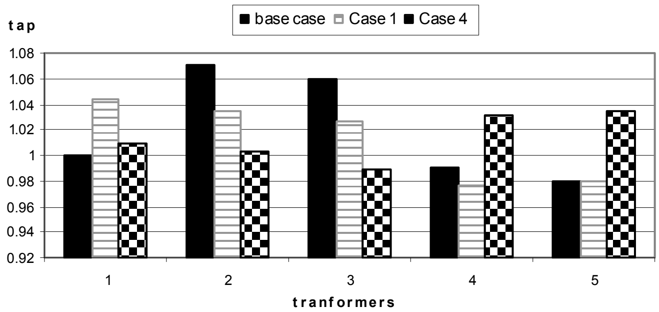

Figure 6. Transformers tap values.

Figures 7, 8 and 9 show the relevant variables in boundary transformers (Q/P ratio or tangent variable, and active and reactive power flows, respectively). The allowed tangent band is fixed on 0.33 as upper limit, and 0 as lower limit. These are similar to the ones imposed by the Spanish regulation [8], being the most restrictive in terms of reactive power flows between the networks operated by the TSO (400 and 220 kV) and DSOs (132 kV and lower voltage levels).

Notice that the reactive power flow constraints are required to obtain reasonable reactive power flow patterns in deregulated power systems with separation of transmission and distribution activities, as shown in Figure 7. In fact, only in Case 4 all Q/P ratios are within limits. Indeed, active power flows virtually do not change after modifying reactive power flows (Figure 8), so reactive power flow limits on each boundary transformers can be considered constants. In fact, the same behavior observed in Figure 7 in terms of Q/P ratios can be observed in Figure 9 in terms of reactive power flows.

As pointed before, voltages are even reduced in order to meet the reactive power flow constraints, as can be observed in Figures 4 and 9.

Figure 7. Tangent value in boundary transformers.

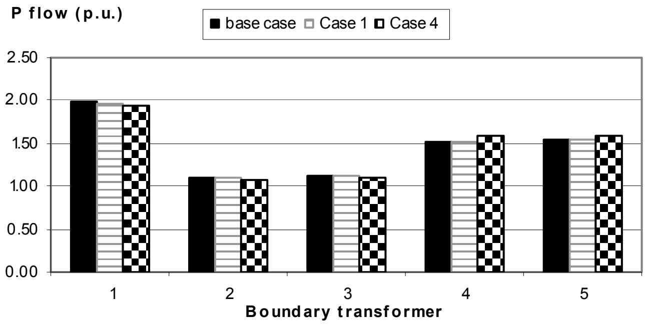

Figure 8. Active power flow in boundary transformer.

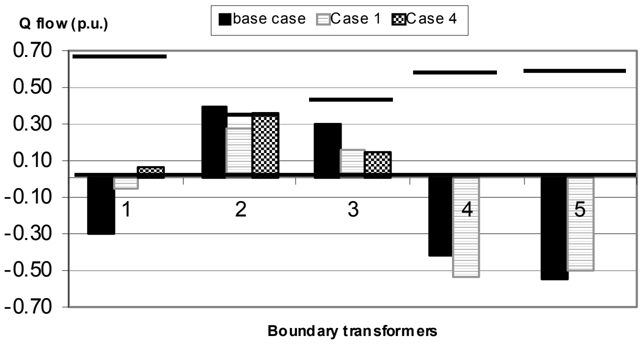

Figure 9. Reactive power flow in boundary transformer.

In conclusion, to satisfy the reactive power flow constraints between transmission and subtransmission (i.e., meshed distribution networks), additional constraints must be imposed in boundary transformers for short-term operation planning. Indeed, the inclusion of new constraints in the optimization process results in higher losses.

B. Sequential optimization (Case 2_1 + Case 3_2 vs case 4)

In case 2_1 the loss minimization problem is first executed in the transmission system. The distribution system is replaced by virtual demands in the boundary buses. The OPF solution corresponding to case 2_1 provides the transmission control values, and they are considered fixed in subsequent distribution system optimizations. It must be mentioned that the scenario obtained by optimizing only the transmission network results in two generators (in the transmission level and distribution level respectively) reaching their reactive power limits when a power flow is run with the transmission optimal controls. This way to act has led to the system to a situation in which two control variables are no longer available for voltage control operation. This fact could harm the operation in future emergencies situations.

The scenario obtained after transmission optimization is taken as the initial scenario in case 3_2, in order to perform the loss minimization process of the subtransmission system. The generator on reactive power limits in the transmission system is considered a PQ bus, i.e., its voltage is released and its reactive power injection is set to the limit. The subtransmission generator is kept as control variable because it is included in the subtransmission system optimization as a control variable. Under these assumptions the subtransmission optimization is performed (Case 3_2), and the resulting scenario is compared with Case 4.

First, the active power losses are analyzed. Table II shows the improvement with respect to the base case and the contribution of both voltage levels (transmission and subtransmission) to the whole system losses. Note that, even in a small network, there are significant differences in loss reduction if the optimization is performed on the whole system or by dividing the OPF problem into two sequential subproblems. Notice that even the transmission losses increase when both networks are optimized separately.

Table II. Active power losses (Case2_1-Case 3_2 and Case 4)

	Whole system Ploss % improvement	% Transmission Ploss	% Subtransmission Ploss
Case 3_2	2.52	68.28	31.72
Case 4	3.02	67.96	32.04

Figure 10. Q/P ratio comparison between case 3_2 and case 4.

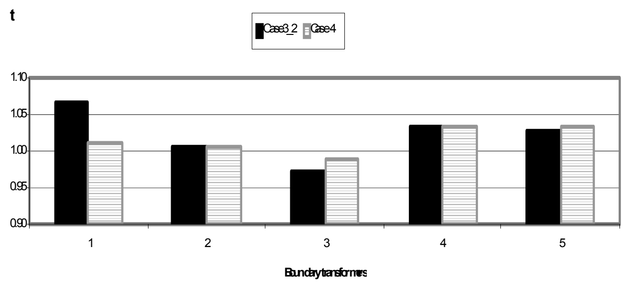

Figure 11. Tranformers tap values in case 3_2 and case 4.

Regarding the Q/P ratio in boundary transformers, both cases presents values that satisfy the reactive power flow constraints, as shown in Figure 9. Besides, voltage set-points of generators are similar in both cases. The main differences appear in transformer taps (Figure 11).

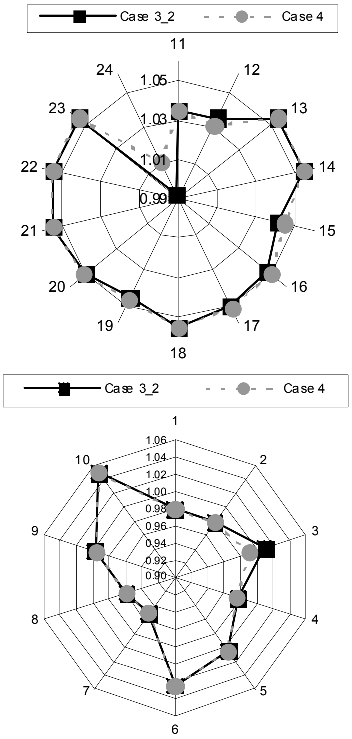

Figure 12. a) Transmission buses voltages; b) Subtransmission buses voltages.

C. *Sequential optimization (Case 2_2 + Case 3_2 vs case 4)*

In this case, the resulting scenario from Case 2_2 provides a set of transmission control variables. These values are considered as data in a whole system power flow analysis. The results are similar to case 2_1, but in this case there are three generators on reactive power limits (two in the transmission system and only one in subtransmission system). Then, the same assumption made in the previous comparison is applied in this section, i.e, the generators on reactive power limits in the transmission network are considered PQ buses, while the subtransmission one is considered a control variable in the subsequent optimization problem (Case 3_2).

The optimum solution is almost the same as the previous one: similar active power losses, control values and dependent variables. In fact, only small differences can be found that are due to the fact that two transmission generators are are no longer available for voltage control operation.

VI. CONCLUSIONS

Several countries have imposed limits on the reactive power flows between transmission and subtransmission or distribution networks. This fact makes it necessary to introduce new restrictions in the tools used for system operation scheduling, traditionally the OPF with a loss minimisation objective.

The results illustrate that the introduction of new reactive power flow constraints on the formulation complicates the OPF problem, though inevitable to satisfy the regulatory requirements.

A logical consequence is observed in the values obtained for the objective function, the network losses. As additional constraints are imposed, greatest losses are obtained compared with a centralized optimization of the whole network.

Another conclusion is that the whole system optimization, including all control variables (transmission and subtransmission) and even reactive power flow constraints, provides better results than if the study is done in a sequential way, considering transmission and subtransmission networks separately. The advantages materialize in lower system losses, better voltage profiles, and even to prevent the loss of generators as voltage control variables.

REFERENCES

[1] Enrique Lobato Miguélez, Ignacio Egido Cortés, Luis Rouco Rodríguez, Gerardo López Camino, "Review: An overview of ancillary services in Spain". Electric Power Systems Research 78 pp. 515–523, 2008.

[2] S. Hao and A. Papalexopoulos, "Reactive power pricing and management" IEEE Trans. Power Syst., vol. 12, no. 1, pp. 95-104, Feb. 1997.

[3] J. W. Lamont and J. Fu, "Cost analysis of reactive power support," IEEE Trans. Power Syst., vol. 14, no. 3, pp. 890–898, Aug. 1999.

[4] J. B. Gil, T. G. S. Roman, J. J. A. Rios, and P. S. Martin, "Reactive power pricing: A conceptual framework for remuneration and charging procedures," IEEE Trans. Power Syst., vol. 15, no. 2, pp. 483–489, May 2000.

[5] G. Chicco, G. Gross, and S. Tao, "Allocation of the reactive power support requirements in multitransaction networks (Republished)," IEEE Trans. Power Syst., vol. 17, no. 4, pp. 1283–1289, Nov. 2002.

[6] J. Barquin, D. Soler, O. Largo, G. Relano, and I. de la Fuente, "On the cost of the reactive power generation and voltage support service," presented at the Bulk Power System Dynamics Control Symp., Santorini,Greece, Aug. 23–28, 1998.

[7] P. Lagonotte, J.C. Sabonnadiere, J.Y. Leost and J.P. Paul, "Structural Analysis of the Electrical System: Application to the Secondary Voltage Control in France", IEEE Trans. on Power Syst.,pp. 479-484, May 1989.

[8] A L. Trigo; J. Riquelme; J. L. Martínez "Treatment of the Reactive Power in the Deregulated Electrical Power Systems in Latin America and Spain" IEEE Latin America Transactions Vol. 7, Iss. 6, pp. 1-8. Dec. 2009.

[9] Evaluation of Reactive Power Planning and Voltage Control Practices in Response to NERC Blackout Recommendation 7a. Transmission Issues Subcommittee of the NERC Planning Committee, May 3, 2005.

[10] "Coordinated voltage control in transmission networks", CIGRÉ, Tech. Rep. c4.602, February 2007.

[11] C. Grigg, P. Wong, P. Albrecht, R. Allan, M. Bhavaraju, R. Billinton, Q. Chen, C. Fong, S. Haddad, S. Kuruganty, W. Li, R. Mukerji, D. Patton, N. Rau, D. Reppen, A. Schneider, M. Shahidehpour, and C. Singh, "The ieee reliability test system-1996. a report prepared by the reliability test system task force of the application of probability methods subcommittee," IEEE Trans. on Power Syst., vol. 14, no. 3, pp. 1010–1020, Aug. 1999.