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Optimization of Area Voltage and Reactive Power Using Interconnection Control of Reactive Power Flow

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***Abstract*— This work presents a method for controlling the interconnection reactive power flows and for managing the voltage and reactive power of the power system optimally. As the voltage and reactive power scheduling in one power system can have significant effects, including extremely negative ones, on the nearby power systems, the need for such control is obvious. The ENTSO-E network code also mandates that the adjacent transmission system operators (TSOs) establish the reactive power flow restrictions on the interconnectors in a uniform manner. A modified single-area reactive power optimization (RPO) method is the foundation of the suggested solution. The reactive power regulation concept included restrictions on the flow of reactive power through the interconnectors. The presented approach does not require complex coordination or exchange of information between the neighboring TSOs, and is easy to implement. The efficiency of the presented method is evaluated using the New England 39-bus system.**

***Index Terms*-- power system interconnections, reactive power control, system operators, voltage control**

I. Introduction

Today, TSOs manage voltage and reactive power in transmission networks almost entirely within their respective spheres of accountability. The potential effects of those voltage and reactive power management measures on the adjacent power systems, whether favourable or unfavourable, are not frequently taken into account. As a result, the interconnection cables may experience high reactive power flows [1]. Reactive power transfers and support between different sections of an interconnected system that are not coordinated can lead to issues with reliability, overload, contingencies, security, and financial constraints as well as put more strain on interconnection connections [2]. One TSO has the opportunity to enhance the situation in the reactive power exchange because there aren't any regulations that are more clearly defined to improve the situation in its own power system at the expense of some other, neighboring TSO. European TSOs, gathered in the ENTSO-E organization, have agreed on the adoption of specific legislation in the common network code concerning the described problem. The recommendation of the ENTSO-E Network code is that the neighboring TSOs interconnected with AC interconnectors define the voltage and/or reactive power flow limits on the interconnectors, in order to use the reactive power resources in the most effective way and ensure adequate voltage control [3]-[4].

Significant study on how these laws are actually implemented in the day-to-day operation of the electrical system is still lacking, though. In the existing research, the issue of reactive power support over interconnections is typically addressed as a component of solutions that coordinate multi-area voltage and reactive power control. The coordinated multi-area RPO techniques typically lead to a wide optimal state of the connected system, although typically without direct control of the reactive power flows at the interconnections.

The established voltage and reactive power control methods could be categorised as non-coordinated or coordinated depending on the degree of cooperation and collaboration amongst the TSOs. [6] looked addressed the effects of non-coordinated Mvar scheduling algorithms in multi-area power networks. The findings suggest that a disorganised approach may raise the operating costs for both the system as a whole and each related sector. On the other hand, coordinated solutions might be categorised as centralised or decentralised. Based on their aims and limits, all connected power systems are optimised using a centralised method in a single control centre [7]–[8]. Centralized techniques have a number of shortcomings even if they offer fair solutions for the entire system [9]–[11]. Authors in[9] emphasize the possible computational burden problems, which immensely increase as the scale of the analyzed power system expands. In [10], problems with the infeasibility are stated. Centralized reactive power optimization in a large multi-area power system would also be very difficult to implement. The main reasons for this are emphasized in [11] as: different legislation in the interconnected countries, competition and conflict of commercial interests between the involved parties, possible lack of reliability of all involved

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components, possible lack of robustness, willingness to share the information, cost and technology performance limitations. In decentralized approach large RPO problem is divided into more sub-problems, one for each independent area. In order to avoid sub-optimality, decentralized optimization scheme requires a certain level of coordination and exchange of information between the involved TSOs. However, such exchange usually includes just the power flow results on the boundary buses. The lack of coordination and collaboration is usually eliminated by using some of the decomposition techniques which can be classified as external network modelling or mathematical decomposition methods. In general, external network modelling methods suffer from sub-optimality, and mathematical decomposition methods require more information exchange and more iterations [12]-[16].

Despite the potential advantages, integrating coordinated multi-area RPO approaches into actual power system operation is a difficult endeavour. However, even if multiple nearby TSOs agreed to implement some of the coordinated multi-area regulation schemes, the problem of reactive power exchange would still not be resolved because other nearby areas would not be covered by the regulation. Despite the drawbacks already noted, Europe's linked power systems nevertheless control voltage and reactive power using a single TSO without considerable inter-area cooperation.

With respect to this, this paper proposes a modification of the standard, single-area RPO model in order to solve the problem of the excessive and unregulated interconnection

reactive power flows. The main assumption is that the reactive power flow limits will be defined for each interconnection line by the included TSOs, as stated in the ENTSO-E Network code concerning the operational security.

The structure of the paper is as follows. In Section 2, a

standard, single-area RPO model is presented. Additionally, the problem of the interconnection reactive power flow control in a multi-area power system is furtherly explained. A possible solution by using a modified single-area RPO method is proposed in Section 3. In Section 4, simulations are conducted to evaluate the effectiveness of the proposed optimization

scheme on the New England 39-bus system. Finally, the conclusions are presented in Section 5.

II. SINGLE-AREA OPTIMIZATION OF VOLTAGE AND REACTIVE POWER

To maintain safe and dependable power system operation, voltage control and reactive power dispatch are essential ancillary services. Voltage regulation is viewed as primarily a local issue since reactive power cannot be efficiently delivered over great distances in a transmission network. The voltage conditions throughout the entire power system can, however, be significantly improved with a centralised and coordinated approach to reactive power dispatch. This will guarantee a safe and cost-effective operation of the electricity system. As a result, for their respective responsibility regions, the majority of TSOs have established a centralised, RPO-based voltage regulating scheme. RPO computations are carried out for brief periods in order to attain the best voltage conditions (from day to hour ahead), or very short (minutes

ahead) terms starting from the foreseen/current state estimation [17]. Hence, the RPO refers to the optimization of a steady-state power system in which the network topology, active power generation, and load demand are considered to be fixed. In general, it can be formulated as a standard optimal power flow (OPF) problem, as given by (1):

$$\min_{u} C(x,u) \quad (1a)$$

$$h(x,u) = 0 \quad (1b)$$

$$g(x,u)\,\Sigma\,0 \quad (1c)$$

Based on this formulation, RPO problem can be derived in various ways. Each TSO defines objective function and optimization constraints based on its own specific requirements. Some of the common objective functions include minimization of the active power losses and/or voltage deviations, maximization of the reactive power reserve, increase of the system voltage stability etc. The detailed formulation of the RPO problem used in this study is given by (2). The objective function is given by (2a), and the related equality and inequality constraints are given by (2b)-(2h).

$$OF = \xi_1 \bullet \sum_{g} {Q_{Gg}}^2 + \xi_2 \bullet \sum_{l} P_{loss-l} + \xi_3 \bullet \sum_{l} \left(|V_i| - |V_{ni}|\right)^2$$
$$g\ \chi\phi\iota_G,\ l\ \chi\phi\iota_L,\ i\ \chi\phi\iota_B \quad (2a)$$

s.t.

$$P_{Gi} - P_{Di} - \sum_{j=1}^{n} P_{ij} = 0 \qquad \{i,j\}\,\chi\phi\iota_B \quad (2b)$$

$$Q_{Gi} - Q_{Di} - \sum_{j=1}^{n} Q_{ij} = 0 \qquad \{i,j\}\,\chi\phi\iota_B \quad (2c)$$

$$\left(P_{ij}\right)^2 + \left(Q_{ij}\right)^2\ \Sigma \left(S_{ij}^{max}\right)^2 \qquad \{i,j\}\,\chi\phi\iota_B \quad (2d)$$

$$\left|V_i^{min}\right|\ \Sigma\ |V_i|\ \Sigma\ \left|V_i^{max}\right| \qquad i\ \chi\phi\iota_B \quad (2e)$$

$$Q_{Gg}^{min}\ \Sigma\ Q_{Gg}\ \Sigma\ Q_{Gg}^{max} \qquad g\,\chi\phi\iota_G \quad (2f)$$

$$Q_{Gv}^{min}\ \Sigma\ Q_{Gv}\ \Sigma\ Q_{Gv}^{max} \qquad v\,\chi\phi\iota_V \quad (2g)$$

$$T_{Tt}^{min}\ \Sigma\ T_{Tt}\ \Sigma\ T_{Tt}^{max} \qquad t\,\chi\phi\iota_T \quad (2h)$$

The power system lines, buses, generators, reactive power sources or loads, and transformers, respectively, are denoted in this formula by the letters L, B, G, V, and T. Transformers are identified by the index t, lines by the index l, buses by the indexes I and j, generators by the index g, and variable sources by the index v. The minimization of the bus voltages |Vi| departures from the nominal values |Vni|, active power losses Ploss-l, and generator reactive power injections QGg are all included in the multi-objective function OF. It is simple to alter the objective function by altering the weight coefficients' values. A bus's active and reactive power balance is represented by equality constraints (2b) and (2c) for each bus i. P_{ij} is the active power flow from bus *i* to bus *j*. Similarly, Q_{Gi} and Q_{Di} are the reactive power generation and demand at the bus *i*, and Q_{ij} is the reactive power flow from bus *i* to bus *j*. In (2d), maximum

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transfer capability of each line is defined as S_{ij}^{max}. $|V_i^{min}|$ and $|V_i^{max}|$ are the minimum and the maximum allowable voltage magnitudes of bus *i*, as shown in (2e). The generator reactive power capacity limits are given by (2f), where Q_{Gg}^{min} and Q_{Gg}^{max} are the minimum and the maximum reactive power output. Similarly, the reactive power capacity of each var source is also limited, as given by (2g). Q_{Gv}^{min} and Q_{Gv}^{max} are the lower and the upper reactive power capacity limits. T_{Tt}^{min} and T_{Tt}^{max}, given by (2h), are the lower and the upper tap position limit of a transformer *t*.

However, by using this RPO formulation in a multi-area power system, without any restrictions on the reactive power exchange, a possibility is open for one TSO to improve the situation in its own power system at the expense of the neighboring TSO. The most straightforward solution of this problem is to limit the interconnection reactive power flows. Therefore, the aim of this paper is to analyze a possible implementation of the interconnection reactive power constraints using a modified RPO model, and its impact on the power system operation. The assumption is that the reactive power constraints will be determined in advance by the neighboring TSOs. Therefore, they are considered to be the optimization input.

Reactive power flow control and interconnection voltage rules are sometimes defined roughly as zero reactive power flow at each interconnection line, for example in [18]. On the other hand, nearby power systems can be regarded as supplementary service providers. Given this, it was possible to maintain the bounds of the reactive power exchange at each interconnection link, which did not necessarily result in the annulment of the interconnection reactive power flows. Naturally, providing this type of reactive power support from one TSO to another would presuppose a sufficient financial reimbursement. In order to avoid relying entirely on the cancellation of the reactive power exchange, the solution model must be universal.

III. MODIFIED SINGLE-AREA RPO FORMULATION REGARDING THE INTERCONNECTION REACTIVE POWER FLOWS

In order to control the reactive power flows on the interconnections in accordance with the agreed limitations, while maintaining the optimal power system operation, the original RPO model, given by (2), had to be modified. A new set of constraints, given by (3a) and (3b), were added to the original set, given by (2b)-(2h). These constraints need to ensure that the reactive power exchange will be in the defined limits on every interconnection link. The constraints (3a) are used to control the reactive power flows in the boundary buses belonging to the optimized area. However, optimization of voltage and reactive power in one power system will surely affect the reactive power flows on both ends of the interconnections. As already mentioned, this could mean that the valid optimization results in one area could be nullified by the optimization results of the neighbouring area. To avoid this problem the constraints are set to always control the reactive power flows in both boundary buses of each interconnection. Therefore, constraints (3b) are used along

$$Q_{ij-c}^{\min} \le Q_{ij-c} \le Q_{ij-c}^{\max} \qquad \{i,j\} \in \Omega_B,\ c \in \Omega_C \quad (3a)$$

$$Q_{ji-c}^{\min} \le Q_{ji-c} \le Q_{ji-c}^{\max} \qquad \{i,j\} \in \Omega_B,\ c \in \Omega_C \quad (3b)$$

In this formulation Ω_C is the set of interconnection lines. The indices of these lines are given by *c*. Q_{ij-c} and Q_{ji-c} are the interconnection reactive power flows calculated at the boundary buses *i* and *j*, respectively. Q_{ij-c}^{min} and Q_{ij-c}^{max} are the minimum and the maximum allowable reactive power flows defined at boundary bus *i*. Similarly, Q_{ji-c}^{min} and Q_{ji-c}^{max} are the minimum and the maximum allowable reactive power flows defined at boundary bus *j*.

Along with the constraints, the objective function also underwent changes. The new objective function (OFmod) is defined as follows: (4). The initial objective function (OF) is referred to in the first phrase (OF) and is described in (2a). The second term is the total of the interconnection reactive power flows' departures from the specified reactive power restrictions' mean values. Calculations of the deviations are made for both boundary buses. The addition of the second term makes the optimization solution more resistant to the ongoing changes in the power system. The weight coefficient 4 determines its effect on the optimization answer. The higher the ω_4 is, the closer the interconnection reactive power flows will be to the mean values of the defined reactive power constraints. In that way, possible changes in the power system are less likely to lead to constraint violations. However, higher ω_4 will also very often lead to higher values of the original objective function (2a). Hence, the weight coefficient ω_4 needs to be carefully determined, based on the specific requirements of each TSO.

$$OF_{\text{mod}} = OF + \omega_4 \cdot \sum_{c} \left(\left|\Delta Q_{ij-c}\right| + \left|\Delta Q_{ji-c}\right| \right) \qquad \{i,j\} \in \Omega_B,\ c \in \Omega_C \quad (4)$$

Where:

$$\left|\Delta Q_{ij-c}\right| = \left|Q_{ij-c} - Q_{ij-c}^{av}\right| \qquad \{i,j\} \in \Omega_B,\ c \in \Omega_C \quad (5a)$$

$$\left|\Delta Q_{ji-c}\right| = \left|Q_{ji-c} - Q_{ji-c}^{av}\right| \qquad \{i,j\} \in \Omega_B,\ c \in \Omega_C \quad (5b)$$

$$Q_{ij-c}^{av} = \frac{Q_{ij-c}^{\max} + Q_{ij-c}^{\min}}{2} \qquad \{i,j\} \in \Omega_B,\ c \in \Omega_C \quad (5c)$$

$$Q_{ji-c}^{av} = \frac{Q_{ji-c}^{\max} + Q_{ji-c}^{\min}}{2} \qquad \{i,j\} \in \Omega_B,\ c \in \Omega_C \quad (5d)$$

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with the (3a) to control the reactive power flows in the neighbouring areas' boundary buses.

In this formulation $|\Delta Q_{ij-c}|$ and $|\Delta Q_{ji-c}|$ are the absolute deviations of the interconnection reactive power flows from the mean values of the defined reactive power constraints. The method for the calculation of these deviations is given by (5). The mean values of the reactive power constraints for both boundary buses are given by Q^{av} and Q_{i-cav}.

I. CASE STUDY

By altering the parameters of the chosen power system components, optimal control of the power system's reactive power and voltage is made possible. These variables are regarded as the control variables for optimization. They typically contain both continuous variables (such as generator voltages) and discrete variables (e.g. transformer tap positions). Consequently, the RPO is a mixed integer nonlinear programming (MINLP) problem by definition. Numerous optimization methods have been proposed and put to the test up until this point in order to solve RPO concerns. The interior point approach, for example, cannot effectively handle both continuous and discrete variables. Until the optimization is finished, discrete variables are typically treated as continuous. The values are then rounded to the closest discrete value. The goal function may rise as a result, or even impossible solutions [19]. Conventional approaches also have the significant disadvantage of consuming a lot of time and resulting in local minima [20]. Genetic algorithms (GA), an evolutionary-based approach, are capable of handling discrete variables [21]. For this reason, the GA [22]-[24] was used to implement the suggested optimization strategies. The Matlab R2013a optimization toolbox's GA solver was used to code and test the optimization models. The Siemens PSS/E 33.5.2 programme was used to code the entire Newton-Raphson power flow algorithm, and the outcomes were then tested.

The power flow method also included the distributed slack bus model that is described in [25]. The advantage of this paradigm is that the slack bus is determined as needed during the iterative load-flow process, rather than beforehand. On the basis of the smallest system power imbalance, the best slack bus, or slack buses, are chosen.

An established New England 39-bus test system was employed to gauge how well the suggested RPO model would perform. As shown in Fig. 1, the system was divided into three related regions.

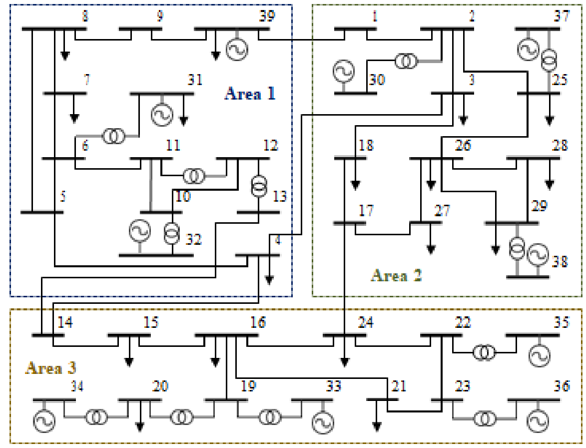

Figure 1. New England 39-bus test system

The assumption is that each area is under control of separate TSO. The impact of the unregulated inter-area reactive power exchange on the area optimization results, as well as the possible benefits of the interconnection reactive power flow control, are demonstrated for two case studies. In the first case study all areas have implemented a single-TSO, non-coordinated RPO schemes. In the second case study two areas have implemented a centralized multi-area RPO scheme, while the third has kept a non-coordinated RPO scheme. Initially, the same objective function, given by (2a), was used for all test scenarios (ω_1=1.0, ω_2=ω_3=0.0). The acceptable bus voltage deviations were set as ±10% of their nominal values.

A. Non-coordinated RPO

The effects of the unregulated interconnection reactive power flows on the outcomes of the area optimization are shown in the first test scenario. Three areas were sequentially optimised. Area 1 was optimised first, followed by Area 2 and Area 3, respectively. Fig. 2 displays the findings for three of these iterations. As can be observed, each area's initial RPO raises the nearby areas' other areas' objective value.

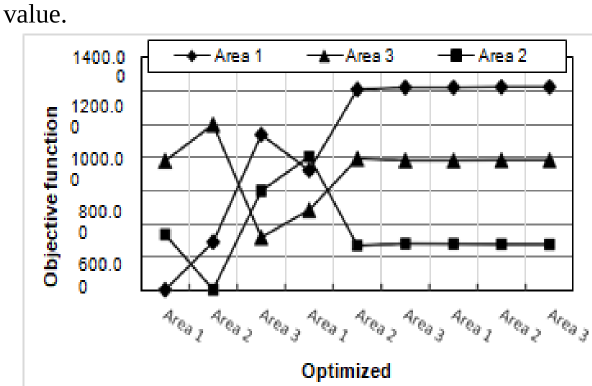

Figure 2. Sequential non-coordinated RPO in a multi-area power system without control of the interconnection reactive power flows

The interconnection reactive power constraints for all boundary buses in the second test scenario were set to 50 Mvar. Utilizing the provided RPO model with an additional set of restrictions (3) (4=0.0), the sequential

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RPO is carried out. The results shown in Fig. 3 show that the RPO model proposed can guarantee that all interconnection reactive power flows adhere to the established limitations. The original interconnection reactive power fluxes are shown by Qij, and the optimised ones by Qij-opt. Additionally, the findings in Fig. 4 demonstrate that in such circumstances, the influence of a non-coordinated RPO on the surrounding areas is greatly diminished.

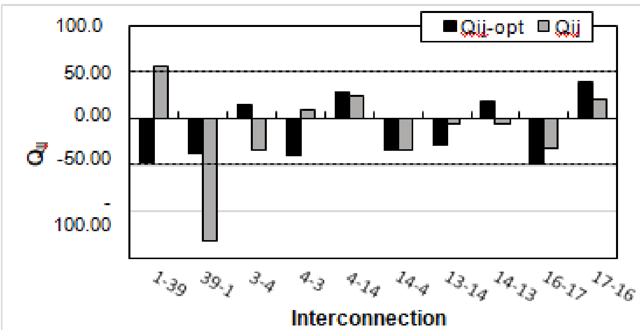

Figure 3. Reactive power flows on the interconnectors before and after the sequential non-coordinated RPO (±50 Mvar; ω_4=0.0)

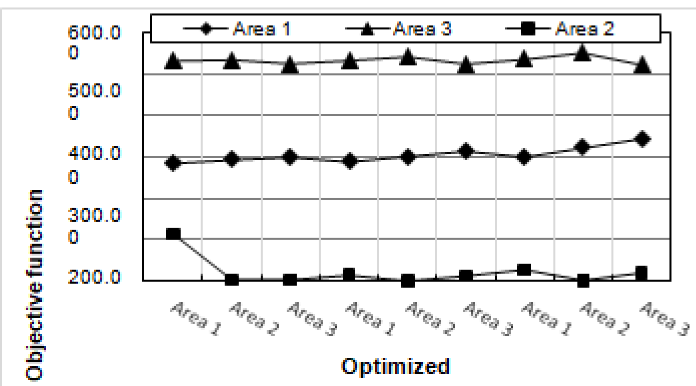

Figure 4. Sequential non-coordinated RPO with constrained interconnection reactive power flows (±50 Mvar; ω_4=0.0)

However, even with satisfied limitations, the inter-area influence can still be substantial if the limits are not specified in such a stringent manner. The findings of the third test case, when the interconnection reactive power limitations were set to 75 Mvar, make this clear. The connectivity limitations are met by utilising the proposed RPO model, as shown by the findings from Fig. 5 (4=0.0), but the results from Fig. 6 demonstrate that each area's influence on the condition of its nearby areas is still noticeable.

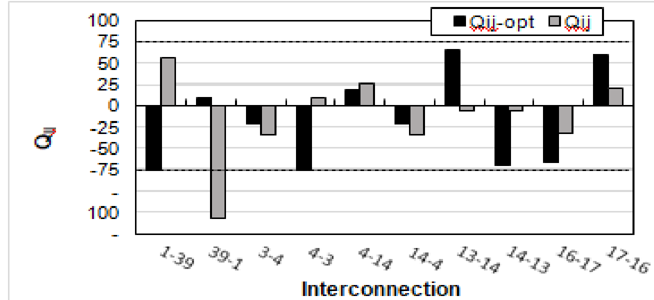

Figure 5. Reactive power flows on the interconnectors before and after the sequential non-coordinated RPO (±75 Mvar; ω_4=0.0)

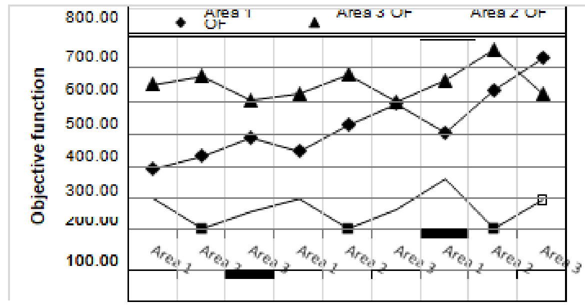

Figure 6. Sequential non-coordinated single-area RPO with constrained interconnection reactive power flows (±75 Mvar; ω_4=0.0)

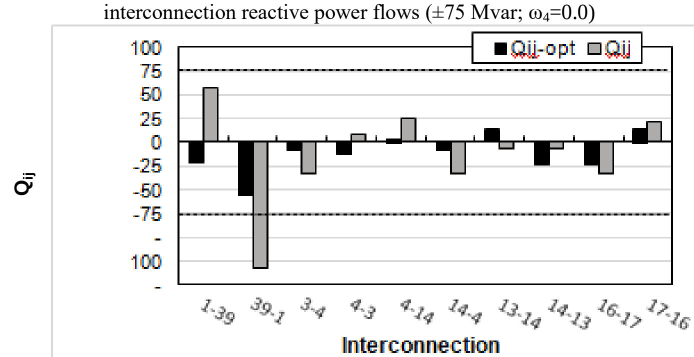

Figure 7. Reactive power flows on the interconnectors before and after the sequential non-coordinated RPO (±75 Mvar; ω_4=1.0)

Using a modified RPO objective function, as explained in (4), might greatly enhance the outcomes in these circumstances. The fourth test case used the given RPO model (4=1.0) with interconnection reactive power constraints of 75 Mvar. The results in Fig. 7 demonstrate that, in comparison to those in Fig. 5, the interconnection reactive power fluxes have significantly decreased. Furthermore, Fig. 8 shows that the inter-area effect is also diminished.

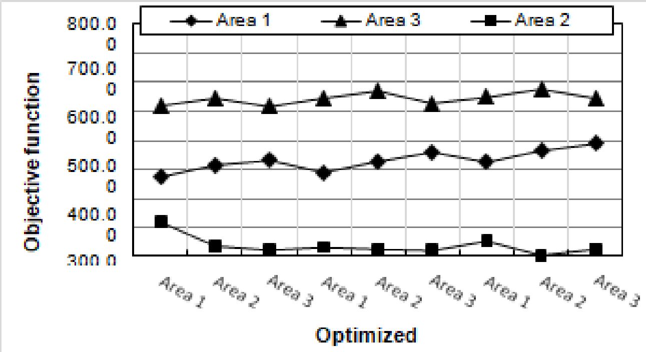

Figure 8. Sequential non-coordinated RPO with constrained interconnection reactive power flows (±75 Mvar; ω_4=1.0)

B. Mixed coordinated and non-coordinated RPO

The problems with the unregulated interconnection reactive power flows could be solved by implementing the coordinated multi-area voltage and reactive power control methods. However, only the edges of the power systems covered by this rule would benefit from this solution. The issues would still exist because it is extremely unlikely that all TSOs in a big, mesh interconnection like the European would take part in the same regulating programme. The outcomes of the second case study are offered to illustrate this.

In the second case study, the RPO model for regions 2 and 3 was a centralised multi-area control method. Without any restrictions on the reactive power flows between them, it was assumed that both areas are optimised centrally. On the other hand, Area 1 has continued to use the uncoordinated (single-area) RPO strategy. Two test case outcomes are shown. Without any restrictions on the interchange of reactive power, areas are sequentially optimised in the first test scenario. Area 1 was optimised initially, followed by the multi-area power system MA 23, which includes areas 2 and 3. Fig. 9's results for three of these iterations show that the optimization of Area 1 raises the value of the objective function for the MA 23, and vice versa.

In the second test case the reactive power constraints were set as ±75 Mvar an all interconnectors between the Area 1 and the MA 23 (ω_4=1.0). This approach significantly reduces the inter-area impact on the objective function values, as can be seen from the results given in Fig. 10.

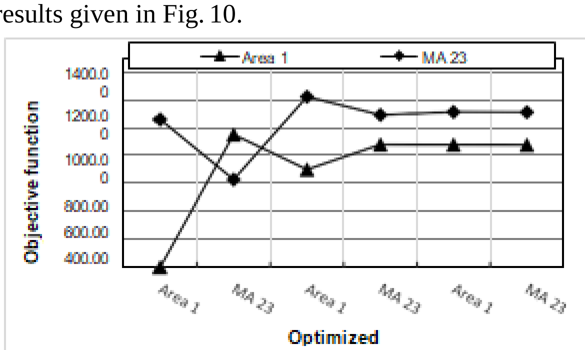

Figure 9. Sequential, mixed coordinated and non-coordinated, RPO without control of the interconnection reactive power flows

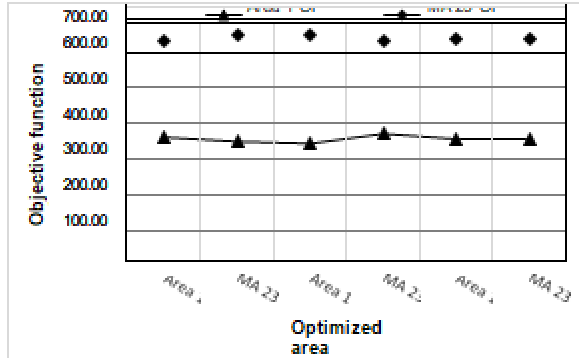

Figure 10. Sequential, mixed coordinated and non-coordinated, RPO with constrained interconnection reactive power flows (±75 Mvar; ω_4=1.0)

II. CONCLUSIONS

This study emphasises the significance of connecting reactive power flow regulation. A proposed approach to the problem is based on the ENTSO-E network code regulation. The essential premise of this regulation is that the adjacent TSOs shall jointly determine the voltage and reactive power flow restrictions on the AC interconnectors. This presumption leads to the addition of a new set of limitations to the traditional RPO model. To further assure the solution's robustness, the objective function is adjusted. The suggested strategy is efficient and straightforward, and it doesn't call for onerous or too complicated information exchange or coordination between the nearby TSOs.

The simulation findings for the New England 39 bus test system show the detrimental effects of uncoordinated reactive power and voltage control and offer a reason for utilising the suggested solution strategy. The results also show that coordinated multi-area control cannot regulate reactive power flows on the AC interconnectors or produce optimal outcomes when some surrounding power systems do not use the same regulation scheme.

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