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Security Constrained Reactive Power Scheduling Considering N-1 Contingency of Transmission Lines

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Abstract- *This paper presents a methodology for reactive power scheduling (RPS) of power system in the form of AC optimal power flow (AC-OPF) problem. The objective function is minimization of system total active power losses. The OPF optimally determines reactive power output of generating units and synchronous condensers, tap-changers ratio, shunt capacitor banks and reactors. The effect of tap-changer is modeled in the active and reactive power flow of transformer. The proposed method grantees secure operation of system in normal operating condition and also in contingency of transmission line outage. The validity of proposed method is studied based on IEEE RTS 24-bus. Results show the capability of suggested AC-OPF for RPS of system in base case as well as contingency of single line outage.*

Keyword: AC optimal power flow (AC-OPF), Active power losses, Contingency, Reactive power scheduling (RPS), Tap changer

1. INTRODUCTION

Reactive power has a significant effect on system security as the buses voltage of network can be directly controlled by reactive power and lack of enough reactive power may results in voltage collapse [1–3].

RPS is studied in some research works. In Ref. [4], the reactive output of synchronous generators and condensers are rescheduled to improve system voltage stability margin without changing the results of economic dispatch. A fuzzy RPS is proposed in Ref. [5] to improve system voltage security and reduce system losses in which the voltage violation of buses and also capability of reactive power compensators are shown by fuzzy sets. A robust OPF is proposed for RPS in which reactive power capability limit is considered in Ref. [6] considering the coupling of reactive power and active power consumption by using the concept of power factor. In Ref. [7], a zonal congestion management method is proposed wherein the zones are determined based on the sensitivity of real and reactive power flow of transmission lines respect to re-scheduling of active and reactive power termed as real and reactive transmission congestion distribution factors. The generators in the most sensitive zones are rescheduled.

A tri-level hierarchical control of voltage and short and very short term RPS is suggested in Ref. [8]. The three levels, i.e. primary, secondary and tertiary regulation are determined by specific control actions which affects the system. It is concluded that an operational coordination between on-line voltage control and off-line RPS is necessary. A successive fuzzy multi-objective method is proposed to minimize system losses and maximize voltage stability margin (VSM) subjected to system constraints [9]. In Ref. [10], the CIGRE models of synchronous generators units is used for contingency scheduling of reactive power based on the capability curves and the reactive power margin of automatic voltage regulator (AVR) states, i.e., normal operation, threshold and loss of voltage control. In Ref. [11], a hierarchical optimization strategy is proposed for energy and reactive power scheduling problem in a photovoltaic-battery microgrid cluster (MGC) operating autonomously, taking the advantage of the decentralized control architecture in multi-microgrids (MMGs). The active power is first determined and then the reactive power control is scheduled by independently considering medium-voltage (MV) and low-voltage levels. A robust methodology is proposed for distribution networks including electric vehicles (EVs) in which energy cost and the voltage deviation are simultaneously minimized subjected to EVs and network constraints [12].

A multi-objective RPS method is proposed for power systems including wind farm (WF) that the reactive power capability of WFs is presented to be scheduled

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for reactive power compensation. The compromise objective functions are: power losses, voltage deviation, and the number of under load tap changing (ULTC) transformer tap variations and operations, all to be minimized [13]. In Ref. [14], a reactive power dispatch model is presented in which both technical and economic aspects related to reactive power dispatch in competitive electricity markets are considered. Considering the coupling of active and reactive power, generation re-dispatch is allowed within a given limit. The reactive power scheduling in the electricity market is studied in references [15-17] wherein technical and economic concerns related to reactive power is considered in the form of single objective and multi-objective reactive power market. The economic aspect is to minimize total payment to the generators for reactive power compensation, while technical aspects are minimizing voltage deviation, minimizing overload index and maximizing system voltage stability margin (VSM). It is noted that in all of papers [15-17], the reactive power market is decoupled from energy market. The work in Ref. [18] emphasizes on dynamic reactive power compensation of wind power plants in a wind power dominated power system. It is concluded that wind power plant is supposed to be used as reactive power compensator. The work in Ref. [19] has solved reactive power dispatch problem using Monte Carlo (MC) simulations. Finally, the paper presented in Ref. [20] solve reactive power dispatch problem in distribution system in the presence of solar PVs using alternating direction method of multipliers (ADMM).

The contributions of this paper are:

1. To formulate OPF problem for RPS in such a way that directly incorporates ULTC transformer ratio as a decision variable, in a straight forward method that can be solve by analytical methods instead of using evolutionary method such as GA, PS, and etc.
2. With the formulation of OPF for RPS problem, the admittance matrix of network (Ybus) is no longer required. It solely requires transmission line DATA. This formulation is so helpful in solving OPF problem, especially in the case of considering N-1 contingency of transmission lines outage.
3. The proposed method determines the reactive power output of generating unit and reactive power compensator and ULTC transformers ratio with the minimum deviation of generating units output from base case.

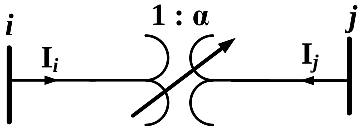

Fig. 1. Single line diagram of ULTC transformer

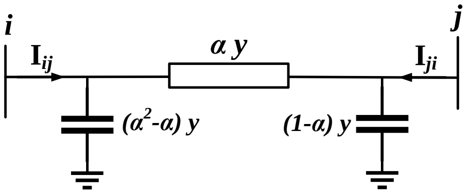

Fig. 2. Equivalent circuit of ULTC transformer

In section two, the proposed RPS is presented. In the third one, the AC-OPF is studied on IEEE 24 bus network and results are analysed. The last section is conclusions.

2. POWER FLOW EQUATION FOR TRANSFORMER WITH TAP-CHANGER

In the following tap-changer transformer and its equivalent circuit are shown in Fig. 1, Fig. 2, respectively.

Based on Fig. 2, the apparent power flow of ULTC transformer from bus *i* to bus *j* (S_{ij}) can be written as:

$$S_{ij} = V_i\, I_{ij}^* = V_i\left(\left(\alpha^2 - \alpha\right) y V_i + \alpha y\left(V_i - V_j\right)\right)^* \quad (1)$$

Based on Eq. (1), the active power flow of ULTC transformer from bus i to bus j (p_{ij}) is the real part of S_{ij} that is calculated as:

$$p_{ij} = \Re\left\{S_{ij}\right\} = \alpha_{ji}^2\, G_{ij} V_i^2 - \alpha_{ji}\, G_{ij} V_i V_j \cos(\theta_{ij}) - \alpha_{ji}\, B_{ij} V_i V_j \sin(\theta_{ij}) \quad (2)$$

Also, based on Eq. (1), the reactive power flow of ULTC transformer from bus i to bus j (q_{ij}) is the imaginary part of S_{ij} that is calculated as:

$$q_{ij} = \aleph\left\{S_{ij}\right\} = -\alpha_{ji}^2\, B_{ij} V_i^2 + \alpha_{ji}\, B_{ij} V_i V_j \cos(\theta_{ij}) - \alpha_{ji}\, G_{ij} V_i V_j \sin(\theta_{ij}) \quad (3)$$

Similarly, the active and reactive power flow of ULTC transformer from bus j to bus i are obtained based on equations (3) to (6) as follows.

$$S_{ji} = V_j\, I_{ji}^* = V_j\left(\left(1 - \alpha\right) y V_j + \alpha y\left(V_j - V_i\right)\right)^* \quad (4)$$

$$p_{ji} = \Re\left\{S_{ji}\right\} = G_{ji} V_j^2 - \alpha_{ji}\, G_{ji} V_i V_j \cos(\theta_{ji}) - \alpha_{ji}\, B_{ji} V_i V_j \sin(\theta_{ji}) \quad (5)$$

$$q_{ji} = \aleph\left\{S_{ji}\right\} = -B_{ji} V_j^2 + \alpha_{ji}\, B_{ji} V_i V_j \cos(\theta_{ji}) - \alpha_{ji}\, G_{ji} V_i V_j \sin(\theta_{ji}) \quad (6)$$

3. REACTIVE POWER SCHEDULING FORMULATION

The proposed RPS is formulated as an AC-OPF problem with the objective function of minimizing system active power losses as follows:

$$Obj\ Function:\ \min\left\{P_{Losses}=\sum_{\substack{i,j=1\\ i\neq j}}^{n}\left(p_{ij}+p_{ji}\right)\right. \tag{7}$$

Subjected to:

$$p_{ij}=G_{ij}V_i^2-G_{ij}V_iV_j\cos(\theta_{ij})-B_{ij}V_iV_j\sin(\theta_{ij}) \tag{8}$$

$$q_{ij}=\frac{y_C}{2}V_i^2-B_{ij}V_i^2+B_{ij}V_iV_j\cos(\theta_{ij})-G_{ij}V_iV_j\sin(\theta_{ij}) \tag{9}$$

where, $\vec{V}_i=V_i\angle\theta_i$ and $Y_{ij}=G_{ij}+jB_{ij}$ and $Y_{ij}=\frac{1}{Z_{ij}}=\frac{1}{(R_{ij}+jX_{ij})}$ and $G_{ij}=\frac{R_{ij}}{R_{ij}^2+X_{ij}^2}$, $B_{ij}=\frac{-X_{ij}}{R_{ij}^2+X_{ij}^2}$, y_C = admittance of shunt capacitor of line. R_{ij} and X_{ij} are respectively, resistance and reactance of line connecting bus *i* to bus *j*. Also, G_{ij} and B_{ij} are respectively, conductance and susceptance of the line.

$$p_{ij}=\alpha^2G_{ij}V_i^2-\alpha G_{ij}V_iV_j\cos(\theta_{ij})-\alpha B_{ij}V_iV_j\sin(\theta_{ij}) \tag{10}$$

$$q_{ij}=-\alpha^2B_{ij}V_i^2+\alpha B_{ij}V_iV_j\cos(\theta_{ij})-\alpha G_{ij}V_iV_j\sin(\theta_{ij}) \tag{11}$$

$$p_{ji}=G_{ji}V_j^2-\alpha G_{ji}V_iV_j\cos(\theta_{ji})-\alpha B_{ji}V_iV_j\sin(\theta_{ji}) \tag{12}$$

$$q_{ji}=-B_{ji}V_j^2+\alpha B_{ji}V_iV_j\cos(\theta_{ji})-\alpha G_{ji}V_iV_j\sin(\theta_{ji}) \tag{13}$$

$$Tap_{ji}^{\min}\le\alpha\le Tap_{ji}^{\max} \tag{14}$$

$$\theta_{ij}=\theta_i-\theta_j \tag{15}$$

$$\theta_i=0\quad for\ i=slack\,bus \tag{16}$$

$$P_{gi}-P_{di}=\sum_{j=1,\,j\neq i}^{n}p_{ij} \tag{17}$$

$$Q_{gi}+Q_{comp\,i}-Q_{di}=\sum_{j=1,\,j\neq i}^{n}q_{ij} \tag{18}$$

$$V_i^{\min}\le V_i\le V_i^{\max} \tag{19}$$

$$\theta_{ij}^{\min}\le\theta_{ij}\le\theta_{ij}^{\max} \tag{20}$$

$$p_{ij}^2+q_{ij}^2\le S_{\mathrm{ij,max}}^2 \tag{21}$$

$$Q_{gi}^{\min}\le Q_{gi}\le Q_{gi}^{\max} \tag{22}$$

$$P_{gi}^{\min}\le P_{gi}\le P_{gi}^{\max} \tag{23}$$

$$\hat{p}_{ij}=G_{ij}\hat{V}_i^2-G_{ij}\hat{V}_i\hat{V}_j\cos(\hat{\theta}_{ij})-B_{ij}\hat{V}_i\hat{V}_j\sin(\hat{\theta}_{ij}) \tag{24}$$

$$q_{ij}=\frac{y_C}{2}\hat{V}_i^2-B_{ij}\hat{V}_i^2+B_{ij}\hat{V}_i\hat{V}_j\cos(\hat{\theta}_{ij})-G_{ij}\hat{V}_i\hat{V}_j\sin(\hat{\theta}_{ij}) \tag{25}$$

$$\hat{p}_{ij}=\hat{\alpha}^2G_{ij}\hat{V}_i^2-\hat{\alpha}G_{ij}\hat{V}_i\hat{V}_j\cos(\hat{\theta}_{ij})-\hat{\alpha}B_{ij}\hat{V}_i\hat{V}_j\sin(\hat{\theta}_{ij}) \tag{26}$$

$$\hat{q}_{ij}=-\hat{\alpha}^2B_{ij}\hat{V}_i^2+\hat{\alpha}B_{ij}\hat{V}_i\hat{V}_j\cos(\hat{\theta}_{ij})-\hat{\alpha}G_{ij}\hat{V}_i\hat{V}_j\sin(\hat{\theta}_{ij}) \tag{27}$$

$$\hat{p}_{ji}=G_{ji}\hat{V}_j^2-\hat{\alpha}G_{ji}\hat{V}_i\hat{V}_j\cos(\hat{\theta}_{ij})-\hat{\alpha}B_{ji}\hat{V}_i\hat{V}_j\sin(\hat{\theta}_{ij}) \tag{28}$$

$$\hat{q}_{ji}=-B_{ji}\hat{V}_j^2+\hat{\alpha}B_{ji}\hat{V}_i\hat{V}_j\cos(\hat{\theta}_{ij})-\hat{\alpha}G_{ji}\hat{V}_i\hat{V}_j\sin(\hat{\theta}_{ij}) \tag{29}$$

$$Tap_{ji}^{\min}\le\hat{\alpha}\le Tap_{ji}^{\max} \tag{30}$$

$$\hat{P}_{gi}-P_{di}=\sum_{j=1,\,j\neq i}^{n}\hat{p}_{ij} \tag{31}$$

$$\hat{P}_{gi}=P_{gi}+\Delta P_{gi} \tag{32}$$

$$-\Delta P_{gi}^{\max}\le\Delta P_{gi}\le\Delta P_{gi}^{\max} \tag{33}$$

$$\hat{Q}_{gi}+\hat{Q}_{comp\,i}-Q_{di}=\sum_{j=1,\,j\neq i}^{n}\hat{q}_{ij} \tag{34}$$

$$V_i^{\min}\le\hat{V}_i\le V_i^{\max} \tag{35}$$

$$\theta_{ij}^{\min}\le\hat{\theta}_{ij}\le\theta_{ij}^{\max} \tag{36}$$

$$\hat{p}_{ij}^2+\hat{q}_{ij}^2\le S_{\mathrm{ij,max}}^2 \tag{37}$$

$$Q_{gi}^{\min}\le\hat{Q}_{gi}\le Q_{gi}^{\max} \tag{38}$$

$$P_{gi}^{\min}\le\hat{P}_{gi}\le P_{gi}^{\max} \tag{39}$$

In Eqns. (24)-(39) the symbol “^” stands for contingency case. Eqns. (8) and (9) are active and reactive power flow of line between bus *i* to bus *j*. Eqns. (10)-(14) are active and reactive power flow of ULTP transformer. As shown in Fig.1, it is assumed that the tap-changer is on the right hand side of transformer connected to bus *j*). Eqns. (17)-(18) are related to nodal active and reactive power balance. Eqns. (19)-(23) are security constraint related to network and generators. Eqns. (24)-(39) have the same explanation of Eqns. (8)-(23) but this time for contingency condition. According to Eqns. (32)-(33), after line outage, the active power output of generators is re-dispatched to meet system demand and thereby the system total losses could different from that of base case.

4. CASE STUDY

The proposed method is studied based on IEEE RTS 24-bus [21]. This network includes five tap changing under load (TCUL) transformers. The minimum and maximum value of tap position is 0.9 and 1.1 ($a\in[0.9,1.1]$). Since there is not any reactive power compensation device in the network, $Q_{comp\ i}$, is not considered as an optimization variable and thereby only reactive power output of generators and tap changer position of transformers are determined in the AC-OPF problem. Also the ΔP_g of each unit is limited to 10% of its active power output determined previously in the base case reactive power scheduling or in the energy market. The AC-OPF RPS is a nonlinear programming (NLP) problem solved by GAMS using CONOPT solver [22]. The proposed method is readily capable of handling *N-1* of generating unit outage. However, in the case study, only contingency *N-1* of transmission lines outage is considered. The results of RPS for base case as well as single line contingencies are reported in Table 1. From this table it can be seen that for the base case the system total active power losses are 14.38 MW. However, for all of contingencies, the system active power losses are greater that of base case (14.38 MW). In the last column of this table, the minimum deviation of generator active power output from the base is reported. For example, in case of Line 3-24 outage, according to equation (25), the maximum deviation of generating units is set to 1.2 percent of its initial value. In other words, for this case, we have $\Delta P_{gi}^{\max} / P_{gi}$ = 0.012. The system total active power after reactive power scheduling of system is 47.44 MW which is greater than that of base case. The candidate lines for contingency are selected based on their flows in the base case. Therefore, the lines with higher active power flow in base case are considered for contingency analysis of RPS. In the 4th column of Table 1, system total reactive power losses is reported. It is noted that for some contingencies such as line 6-10 or line 7-8 outage, the AC-OPF is not converged, meaning that the optimization problem with voltage limit constraint in the range of [0.95,1.05] and active power deviation from base in range [-10,10] percent, the AC-OPF cannot reach to the optimal solution. However, if the voltage limit range is change to [0.9, 1.1], then the optimization is converged.

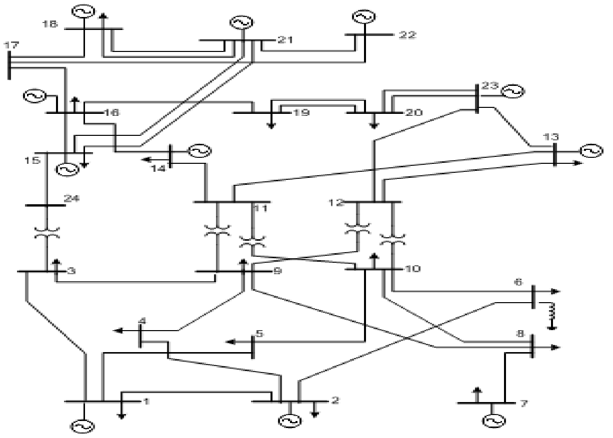

Fig. 3. IEEE RTS 24-bus test system

Table 1. The results of reactive power scheduling for base case and single line outage contingencies

		Total Generation (MW)	Active Power Losses (MW)	Reactive Power Losses (MVar)	$\Delta P_{gi}^{\max} / P_{gi}$ (%)
Base case		2864.38	14.38	430.9	-
Contingency: Line Outage	1-5	2874.43	24.43	408.5	0.5
	3-24	2897.44	47.44	258.2	1.2
	9-11	2868.58	18.58	371.9	0.2
	10-11	2880.07	30.1	376.8	0.7
	12-23	2872.82	22.82	402.6	0.3
	15-24	2867.09	17.09	384.4	0.1
	16-17	2866.53	16.53	443.9	0.08
	17-18	2865.37	15.37	437.3	0.1
	20-23	2865.36	15.36	440.6	0.1

Table 2. The tap position transformers in RPS

		Trans 3-24	Trans 9-11	Trans 9-12	Trans 10-11	Trans 10-12
Base case		1.02	1.00	1.10	0.96	1.05
Contingency: line outage	1-5	1.04	1.01	1.10	0.94	1.02
	3-24	-	0.91	0.96	1.00	1.07
	9-11	1.02	-	1.02	1.04	0.99
	10-11	1.03	1.10	0.98	-	0.95
	12-23	1.04	1.05	0.98	1.04	0.98
	15-24	0.90	1.03	1.09	0.98	1.04
	16-17	1.02	0.99	1.10	0.96	1.06
	17-18	1.02	1.00	1.10	0.96	1.05
	20-23	1.02	1.00	1.10	0.95	1.06

It is observed that all voltage of are near 1.1 p.u., showing extra reactive power conditions in the system and thereby increasing the buses voltage of system to the extreme level of 1.1 p.u. However, this range of voltage is not acceptable in real power systems. In such cases, the operator of system is supposed to compensate reactive power of system by switching system reactors or even by switching of lines which are in the under surge impedance loading (SIL) condition so that the proposed RPS is converged with voltage limit constraint in the range of [0.95, 1.05]. On the contrary, if the optimization is converged with the voltages near to 0.9 p.u., it means that the system reactive power is insufficient. In such circumstance, the system operator must switch capacitor banks so that RPS can be converged with minimum voltage limit 0.95.

If the voltage profile is not improved after switching of capacitor banks, the system operator should ultimately improve system voltage profile by load shedding. The tap position of all five ULTC transformers of system is reported in Table 2. According to this table it can be inferred that the proposed RPS problem can be converged in contingency of ULTC transformer outage. In such cases, since one of effective reactive power scheduling factor (a ULTC transformer) is lost, the problem is usually converged with more active power losses. For example, for contingency of ULTC transformer 3-24 outage, the system active power losses are 47.44 MW which is three times greater than that of base case.

5. CONCLUSIONS

In this paper RPS is proposed in which ULTC transformers, as the key factor in RPS, are included. The system total active power losses are minimized while all system technical limits are considered. The proposed method is converged with the minimum deviation of generating unit active power from their base case. In the case of not converging, the system reactive power insufficiency/surplus should be compensated by connecting capacitor banks/reactors of system or considering them as variables that are determined in the optimization problem. This matter should be carefully considered during reactive power planning of network.

Dependent to the policy of system operator, if DGs, WTs and PVs have the capability of operating in voltage control mode (as PV bus), the proposed method can incorporate them in reactive power scheduling problem. But in PQ model of DGs, WTs and PVs, they are not participated in the reactive power scheduling problem. It is noted that the nonlinear and non-convex terms due to trigonometric functions causes the OPF problem of reactive power scheduling, to be non-convex which results in trapping in local minimum or even not converging in large size power systems. However, the proposed method can be convexified by using convexification methods such as second order cone (SOC) or quadratic convex relaxation (QCR) methods to reach *inexact* but *global* optimal solution.

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