Congestion Management with Dynamic Line Ratings Considering Network Imbalance

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Congestion Management with Dynamic Line Ratings Considering Network Imbalance

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***Abstract*—Dynamic Line rating can be used as a temporary alternative to manage congestion in networks that have high penetration of renewable generation. Key factors for implementing dynamic line ratings in scheduling and planning are network imbalance constraints. Modern power systems are expected to have some degree of imbalance even at the transmission level due to the presence of embedded generation and uncoordinated electric vehicle charging. This paper presents a new mathematical framework to generalize the extended conic quadratic optimal power flow with dynamic line rating in the context of three-phase load flow formulation. Extended cases were studied and results indicate that the proposed approach can be well fitted to unbalanced operating conditions when each phase of the system is considered separately with mutual coupling between phases. Dynamic line rating (DLR) proved to provide considerable benefits in unbalanced networks with no adverse effects on voltage imbalance.**

***Index Terms*—dynamic line ratings, optimal power flow, unbalanced networks.**

I. Introduction

Network congestion is an undesirable result of insufficient availability of network capacity which leads to inequitable allocation of available network capacity among market participants. In networks with a high proportion of renewable energy generators, network congestion may also lead to curtailment of renewable generation. Conventional congestion management methods involving redispatch or generation management [1],[2] can result in suboptimal scheduling of generators. Network based measures [3] are more likely to manage congestion without curtailing generation but it also depends on congestion being localized and the network topology allowing power flows to be diverted through non congested areas.

In our previous work [4],[5] we have proposed incorporation of dynamic line ratings (DLR) into dispatch decisions by utilising a smart grid infrastructure to relax transmission line thermal constraints thus temporarily releasing latent network capacity. This is possible since traditional line thermal ratings are calculated under worst case assumptions for ambient weather and temperature conditions which rarely occur in practice. DLR is calculated based on the relationship between temperature and ampacity outlined in IEEE Std. 738-2012 [6]. Utilities have traditionally used multiple thermal limits for different weather conditions but DLR is a more advanced method used in modern power systems and is implemented in real time. Dynamic ratings can provide a significant increase in the normal and emergency operational flexibility of power transmission systems and defer investments [4],[5]. The benefit of DLR over conventional congestion management approaches is that it can potentially release latent capacity dynamically rather than relying on generation curtailment and demand reduction in congested parts of a network. DLR is mainly applicable for short to medium length lines where thermal capacity as opposed to stability limit is the limiting factor in transporting power.

In modern electricity networks, voltage imbalance has become common due to a number of factors such as presence of single phase distributed generation (DG) including renewable generation, random charging of plug in electric vehicles and un-transposed lines [7-9]. While a network imbalance is more common at the distribution level studies [10] show that imbalance may also occur at the transmission level when there are short un-transposed lines although they are rare. The current flow asymmetry may lead to overcurrent in individual phases of transmission lines which could potentially lead to different levels of congestion in each phase. The presence of micro-grids and imbalances at the point of common coupling can also lead to unbalanced loads at the transmission level [8].

Due to the increasing importance of imbalance considerations, there has been research to develop three-phase unbalance power flow equations [9],[11]. However, the most of the optimal dispatch and scheduling problems for unbalanced networks focused on radial distribution networks [12],[13].

The proposed approach obtains a generalized three phase expression for extended conic quadratic (ECQ) optimisation technique [14] which includes mutual coupling due to unbalanced systems as well as dynamic line rating. The extended conic quadratic (ECQ) approach has the advantage of transforming the highly nonlinear optimal dispatch problem into a problem with mostly linear constraints. The main contribution of this paper is to develop a framework for three phase power flow constraints with dynamic line rating and investigate the effect of applying DLR to each phase independently. Another unique feature of this formulation is that it models the risk due to DLR as a discrete stochastic penalty function which replaces the deterministic thermal constraints with dynamic constraints.

The rest of the paper is organized with section II presents the detailed formulation. Section III presents results and Section IV concludes the findings.

II. Formulation of OPF-ECQ with Unbalanced Constraints

The incorporation of DLR into a balanced three phase optimal dispatch formulation is presented in our previous work in [4],[5]. This approach was modified to include unbalanced systems where the major consideration is the mutual coupling between phases. The per-phase power flow equations for balanced systems have to be replaced by either the sequence component frame [9] or the phase frame [11] which considers each phase instead of sequences. Abdel Akher et al. [9] developed a sequence component based method for the solution of the three-phase power-flow problem and showed that results are identical to those obtained by using phase components. This indicates the suitability of either method. In this paper, phase component methods applied to the ECQ approach are described. Three phase power balance equations for each phase considering flows due to mutual coupling are given in (1) and (2) [11].

$$P_i^x = \sum_{k=1}^{n} \sum_{m \in \{a,b,c\}} \left[V_i^x V_k^m G_{ik}^{xm} \cos\left(\delta_i^x - \delta_k^m\right) + V_i^x V_k^m B_{ik}^{xm} \sin\left(\delta_i^x - \delta_k^m\right) \right] \quad (1)$$

$$Q_i^x = \sum_{k=1}^{n} \sum_{m \in \{a,b,c\}} \left[V_i^x V_k^m G_{ik}^{xm} \sin\left(\delta_i^x - \delta_k^m\right) - V_i^x V_k^m B_{ik}^{xm} \cos\left(\delta_i^x - \delta_k^m\right) \right] \quad (2)$$

where x is the phase and i is the node. The ECQ transformations are then applied and this yields linear equations for the power balance constraints as in (3) and (4).

$$P_i^x = \sqrt{2} G_{ii}^{xx} u_i^x + \sum_{\substack{k=1 \\ k \neq i}}^{n} \left[G_{ik}^{xx} R_{ik}^{xx} + B_{ik}^{xx} T_{ik}^{xx} \right] + \sum_{k=1}^{n} \sum_{\substack{m \in \{a,b,c\} \\ m \neq x}} \left[G_{ik}^{xm} R_{ik}^{xm} + B_{ik}^{xm} T_{ik}^{xm} \right] \quad (3)$$

$$Q_i^x = -\sqrt{2} B_{ii}^{xx} u_i^x - \sum_{\substack{k=1 \\ k \neq i}}^{n} \left[B_{ik}^{xx} R_{ik}^{xx} - G_{ik}^{xx} T_{ik}^{xx} \right] - \sum_{k=1}^{n} \sum_{\substack{m \in \{a,b,c\} \\ m \neq x}}^{c} \left[B_{ik}^{xm} R_{ik}^{xm} - G_{ik}^{xm} T_{ik}^{xm} \right] \quad (4)$$

If x is not equal to m then the terms within the brackets represent the mutual coupling terms in the power balance equations. In addition, the rotated conic quadratic constraints must be written for three phase formulation as shown in (5) and (6).

$$\left(R_{ik}^{xm}\right)^2 + \left(T_{ik}^{xm}\right)^2 = 2 u_i^x u_k^m \quad (5)$$

$$-\gamma\pi + \delta_i^x - \delta_k^m = \tan^{-1}\left(\frac{T_{ik}^{xm}}{R_{ik}^{xm}}\right) \quad (6)$$

The value of γ is a constant that depends on the phases (x and m) between which the coupling is being considered and is given by Table I. The addition of –γπ is not part of the standard ECQ formulation and is necessary as the inverse tan function will normally yield an angle between -90º and 90º. However, when the angle difference is between separate phases, the angle difference will exceed 90º. The addition of –γπ does not affect the calculation of gradient and hessian which are identical to the standard ECQ formulation. The square of the current magnitude from node i to n for phase p can be determined as a linear constraint in ECQ form (7).

TABLE I. Value of γ

		m		
		A	***B***	***C***
x	***A***	0	1	-1
	B	-1	0	-1
	C	1	1	0

$$\left|I_{in}^{p}\right|^2 = \sum_{\substack{q \in \{a,b,c\} \\ q' \in \{a,b,c\}}} \begin{bmatrix} \left(A_1 + B_1 + C_1 + D\right) R_{ii}^{qq'} - \left(A_1 - B_1\right) R_{in}^{qq'} \\ -\left(A_1 - C_1\right) R_{ni}^{qq'} + A_1 R_{nn}^{qq'} \\ +\left(A_2 + B_2 - C_2\right) T_{ii}^{qq'} - \left(A_2 + C_2\right) T_{in}^{qq'} \\ -\left(A_2 - B_2\right) T_{ni}^{qq'} + A_2 T_{nn}^{qq'} \end{bmatrix} \quad (7)$$

where

$$A_1 = \left(g_{in}^{pq} g_{in}^{pq'} + b_{in}^{pq} b_{in}^{pq'}\right); A_2 = \left(g_{in}^{pq} b_{in}^{pq'} - g_{in}^{pq'} b_{in}^{pq}\right)$$

$$B_1 = \frac{b'^{pq}_{in} b_{in}^{pq'}}{2}; C_1 = \frac{b_{in}^{pq} b'^{pq'}_{in}}{2}; B_2 = \frac{g_{in}^{pq} b'^{pq'}_{in}}{2} C_2 = \frac{g_{in}^{pq'} b'^{pq}_{in}}{2}; D = \frac{b'^{pq}_{in} b'^{pq'}_{in}}{4}$$

Alternatively, phase components may be replaced by sequence components. However, the sequence loads are non-linear functions of phase load and sequence voltages. Using ECQ transformations does not linearize the expressions for sequence loads. Also, further constraints would also be necessary to relate phase and sequence variables. Thus the phase frame was preferred over the sequence component frame.

III. Case Studies

This section describes the effect of introducing imbalance between phases on network congestion and the subsequent effectiveness of DLR in alleviating the congestion. Network imbalance can occur at the transmission level if the loads in all three phases are not balanced or if there are un-transposed lines. For the purposes of modelling it was assumed the phases are at a height of 24 m and the spacing details are in Table II.

TABLE II. Distance between phases

	Phase A	Phase B	Phase C
Phase A	0 m	6 m	12 m
Phase B	6 m	0 m	6 m
Phase C	12 m	6 m	0 m

All case studies were carried out on the IEEE 14 bus test system [15]. The total load was assumed to be the same as described in the data for the IEEE 14 bus system. However, the distribution of the load between the three phases was determined randomly with different levels of imbalance.

The level of congestion is measured by the volatility in locational marginal prices (LMP) between nodes which are found from the Lagrange multiplier associated with the real power balance constraint. Equation (3) represents the real power balance constraint for each phase of each node. Since there are separate power balance constraints for each phase, there are separate LMP for each phase. The term LMP_V is defined in [4] and quantitatively determines level of congestion by comparing the average LMP to an uncongested base case.

A. Transposed case

For a transposed system with unbalanced loads, the variation of LMP_V in each phase with and without DLR against the load imbalance is shown in Fig 1. The load imbalance is the average of the difference in relative loading between all possible combinations of any two phases.

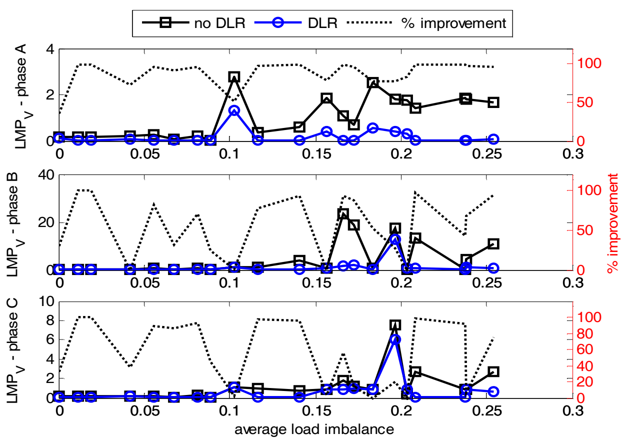

Figure 1. Variation of LMP_V in each phase with load imbalance for DLR and non DLR cases for transposed case

The percentage improvement in LMP_V from the no DLR case is also shown in Fig. 1. The LMP_V without DLR represents the initial level of congestion in the system. The total load is maintained constant for all levels of imbalance and it is observed that as imbalance increases, the congestion in phase A increases steadily. Phase B and C show relatively less increase in congestion. When the imbalance is low, there is adequate spare capacity so that congestion does not occur. Phase A has the highest percentage of load when imbalance increases thus leading to a steady increase in congestion. As imbalance increases, load distribution is transferred from phases B and C to phase A thus increasing congestion in A while reducing congestion in phases B and C. The level of congestion is low but imbalance induced congestion takes effect for levels of imbalance where average load difference between phases is greater than 0.1. For these levels, DLR is seen to be effective in reducing congestion in all phases when congestion is high.

For most cases the first order optimality has a value of 2 – 3. While this is adequately low to yield a result close to optimum, there may be slight error-factor in Lagrange multipliers at the optimum which are used to calculate LMP_V. DLR is still consistent in reducing LMP_V thus the relative error does not affect the conclusion. The constraint violation for most scenarios is between 10^{-4} and 10^{-7} for three phase power flow which is adequate to satisfy most constraints to an acceptable level. The implementation of DLR does not appear to have any noticeable effect on the level of voltage imbalance. Fig. 2 shows an example of implementing DLR in an individual phase compared to all phases.

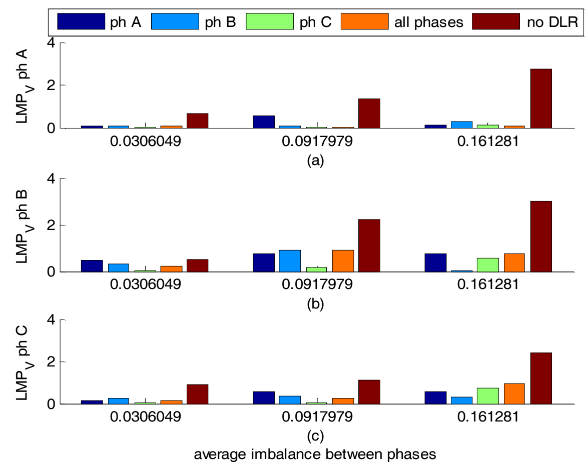

Figure 2. Variation of LMP_V in each phase when individual phases have DLR for a transposed system (a) phase A LMP_V (b) phase B LMP_V (c) phase C LMP_V

The phase with DLR implemented is denoted by the legend in Fig. 2. These are typical cases at different levels of network imbalance. Implementing DLR will increase the self as well as mutual flows in a line which will in turn influence mutual flows in other lines. Thus under congestion it is possible for phases with DLR to transfer some power to phases without DLR and thus reduce congestion to some extent. The corresponding line flows for an average imbalance of 0.0918 are shown in Fig 3. In Fig. 3, when DLR is implemented in all phases, the optimal dispatch configurations allocated the highest line flows to phase C. This is also reflected in Fig. 2 since implementing DLR in phase C has the highest impact in reducing LMP_V in other phases. The improvement from relaxing phase C appears to be even higher than the case with all phases relaxed. While this may not necessarily occur in practice it merely indicates that implementing DLR in phase C is most effective.

B. Un-transposed case

For the un-transposed case approximately 30% of the cases had a constraint satisfaction greater than 10^{-3} while for the transposed case, all the cases have constraint satisfaction less than 10^{-3}. For these cases, there is a high likelihood that the optimal solution as well as LMP_V values will be relatively less accurate. However, the effect of DLR was still evident even when constraint satisfaction had a degree of inaccuracy. There is a greater imbalance in the flows in each line compared to the transposed case which is indicative of the fact that un-transposed systems have more mutual coupling.

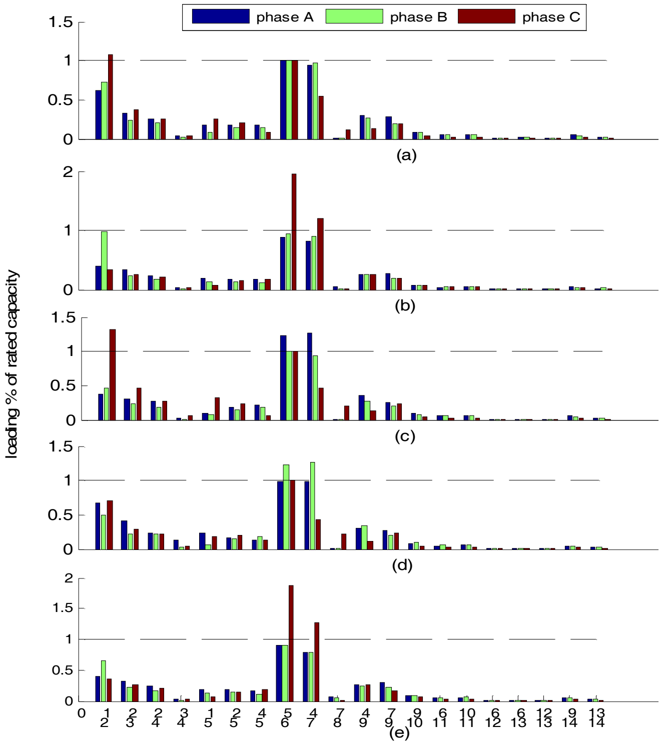

Figure 3. Line flows for transposed system, average imbalance of 0.0918 (a) No DLR (b) DLR in all phases (c) DLR in phase A (d) DLR in phase B (e) DLR in phase C

The variation and improvement in LMP_V is plotted in Fig. 4 only for results with a constraint satisfaction less than 5 x 10^{-4}. For these cases it is observed that the congestion is low for imbalance higher than 0.25.

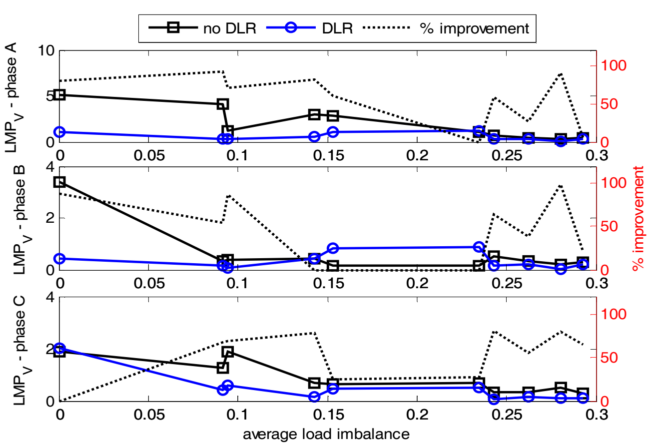

Figure 4. Variation of LMP_V in each phase with load imbalance for DLR and non DLR cases for untransposed case only for cases where constraint satisfaction is less than or equal to 5x10^{-4}

For imbalances lower than 0.25, phases A and B have similar levels of congestion while phase C has less congestion. Phase B has the highest amount of mutual flows from the other two phases and the phase A has the highest proportion of load. All three phases experience similar reduction in congestion due to DLR. Between imbalance levels of 0.15 to 0.24, the improvement due to DLR is at the minimum for all three phases as the initial level of congestion is low. In contrast to transposed systems, it was also observed that the zero sequence voltage increase under DLR appears to vary from 35 – 40% and depends on the level of load imbalance. This indicates that DLR is encouraging imbalance to allow further power flows through phases with slightly less loading. The flows in each phase will be unbalanced when the lines are un-transposed as some phases will experience higher mutual flows depending on tower configuration. Fig. 5 shows the effect of implementing DLR in individual phases for an un-transposed system with corresponding line flows for an imbalance of 0.103 in Fig. 6.

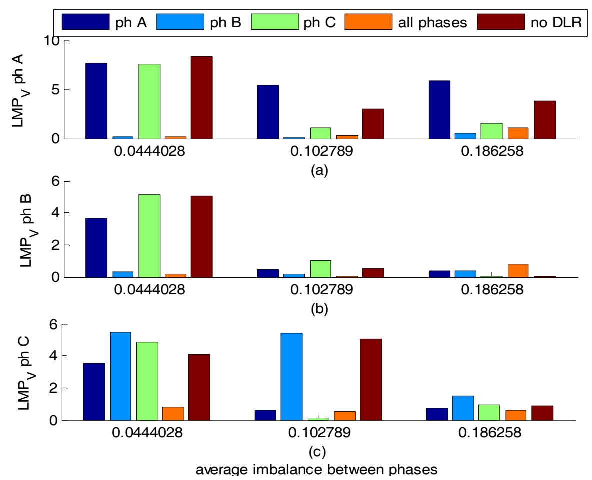

Figure 5. Variation of LMP_V in each phase when individual phases have DLR for an untransposed system (a) phase A LMP_V (b) phase B LMP_V (c) phase C LMP_V

In some cases in Fig. 5, implementing DLR increases the value of LMP_V compared to the no DLR case. This is due to the relatively higher constraint violation and first order optimality for the un-transposed case compared to the transposed case. This leads to errors in the LMP at the solution. In a practical scenario, this would indicate that DLR does not necessarily reduce congestion significantly since LMP_V under dynamic line rating is unlikely to be greater than LMP_V without DLR. Generally, for the un-transposed case there is a significantly different effect on LMP_V depending on the phase on which DLR is implemented. This is expected since the effect of mutual flows between phases will be unequal as compared to the transposed case. Thus, phase selection is more important for un-transposed cases to realise the benefits of DLR.

Thus, the results in this section support the argument of the benefits of DLR can also be realized in unbalanced systems. The improvement in congestion by DLR appears to be independent of the level of imbalance even though higher imbalance can lead to greater congestion in phases where more load is allocated. Additionally, DLR showed a negligible effect on the level of voltage imbalance. The solution of the problem is less robust when un-transposed unbalanced systems are considered. However, most transmission level imbalances are small and usually due to load imbalance at the point of common coupling. Thus un-transposed system solution capability is required on rare occasions.

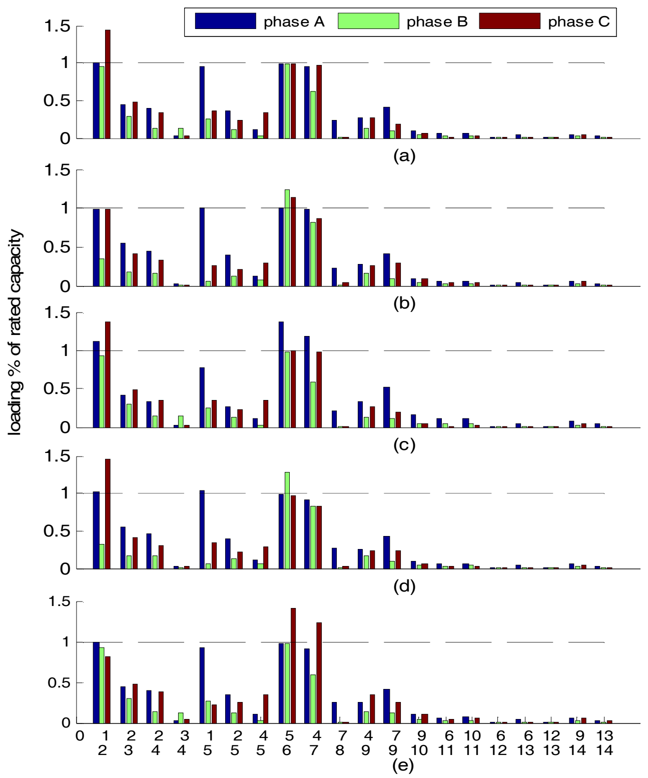

Figure 6. Line flows for untransposed system, average imbalance of 0.103 (a) No DLR (b) DLR in all phases (c) DLR in phase A (d) DLR in phase B (e) DLR in phase C

Implementing DLR in a single phase as compared to all phases can be an alternative in unbalanced systems. The effect of relaxing a single phase affects power transfer from phases with DLR to phases without DLR by changing the mutual flows. In un-transposed cases phase selection appears to be important since certain phases may be more favourable than others for DLR. The nonlinear nature of self and mutual flux linkages between transmission lines makes it challenging to predict accurately the detailed effects of implementing DLR in individual phases.

IV. Conclusion

This paper proposed a mathematical framework to solve three phase unbalanced optimal power flow by generalizing the extended conic quadratic formulation to assess dynamic line rating effects with network imbalances resulting from the effect implementation of DLR independently to phases. The proposed approach displayed better convergence transposed unbalanced networks compared to un-transposed cases.

Dynamic line rating was successful in significantly reducing the level of congestion in the test cases with no adverse effects on voltage imbalance. Relaxing phase thermal constraints individually has shown some benefits in reducing congestion but the nonlinearity makes it challenging to model and predict. As networks evolve in complexity, it is likely that some degree of imbalance will be visible at the transmission level which dynamic line rating decisions will have to account for. The approach proposed in this paper is a robust evaluating technique for optimal dispatch of generation with dynamic line ratings in unbalanced transmission systems.

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