Master's Thesis

A NEW APPROACH FOR CORRECTIVE AND PREVENTIVE CONTROL TO UNSOLVABLE CASE IN POWER NETWORKS HAVING DERs

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Department of Electrical Engineering and Computer Science

College of Engineering

Seoul National University

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指導敎授 尹 容 兌

이 論文을 工學碩士 學位論文으로 제출함

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Abstract

A NEW APPROACH FOR CORRECTIVE AND PREVENTIVE CONTROL TO UNSOLVABLE CASE IN POWER NETWORKS HAVING DERs

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In recent times, Korean power system operating conditions have gradually approached an upper limit. When a contingency occurs, the power system may have unsolvable cases for which a power flow solution does not exist. Different from the cases of bad initial guesses or the solutions are too close to the solvability boundary in which numerical methods such as optimal multiplier or continuation power flow method can be applied, in unsolvable cases, the only way to restore solvability would be structure modifications. In this thesis, a new approach for corrective and preventive control to such cases is proposed. The strategy is implemented in two steps: (i) finding any solution regardless its feasibility (Corrective control); (ii) for the infeasible solution, make it feasible with additional modifications to voltage at load buses having Distributed Energy Resources (Preventive control). The test case built based on the peak load profile of 2008 in Korea by KEPCO including 1336 buses is analyzed. The most important contribution of the proposed method is ability to prevent voltage collapse. In addition, a new approximation technique which is able to capture high non-linear factors is introduced. Finally, since reactive power compensation is optimized to restore solvability, all demands are met- in other words, no blackouts happen. The proposed method has been being integrated in the load flow program designed by power 21 Corporation.

Keywords: Convergence, DERs, Newton-Raphson method, power flow, PTDFs, solvability.

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List of Symbols

A An $n \times n$ matrix of real numbers

x A point in the n-dimensional Euclidean space E^n

$F(x)$ A nonlinear function mapping E^n into E^n

$Q_{l(ij)}$ The reactive power flows through the line l_{ij} between bus i and bus j

V_i, δ_{ij} The voltage magnitude and angle at bus i

G_{ij}, B_{ij} The conductance and the susceptance of the line l_{ij}

p_{ij-k} PTDF of the reactive power through the line l_{ij} with respect to the reactive power of load bus k

ΔQ_i Deviation of reactive power at bus i

n_1 Number of buses which belong to tier 1

n_N Number of buses which belong to SOI

ΔQ_{ss-i} The amount of reactive power change due to SS at bus i

ΔQ_{ss-ij} The deviation of reactive power transferred from bus i to bus j

$[\Delta Q], \Delta$ The origin mismatch vector

$[\Delta Q^{'}], \Delta^{'}$ The new mismatch vector after SS control

α_{ij} The attenuation factor related to bus i and bus j

$[J_V]$ The corresponding part of Jacobian matrix

Chapter 1

Introduction

1.1 General

Recently load demand and power transfers between utilities have been increasing significantly. This trend has raised concerns about system voltage security. Voltage collapse has been deemed responsible for several major blackouts [1]. In order to further understand voltage phenomena, the divergence problem of power flow is needed to be scrutinized. A significant number of researchers have proposed various methods to deal with this problem [2-6]. Different from other numerical methods, in order to avoid singular Jacobian matrix in the proposed method, the system network where no solution exists, is changed by adjusting its physical conditions until there is a solution to the network. In particular, switched shunts are controlled to rearrange the distribution of reactive powers in order to reduce mismatch in Newton-Raphson (N-R) iterations. Eventually, a good convergence characteristic is achieved.

The solution achieved in the Corrective control phase may be an infeasible one, i.e. violates constraints like voltage limits. One of the most popular remedies to eliminate these violations is using compensation devices such as capacitor banks. However, these devices have some disadvantages [7]. Therefore, using Distributed Renewable Resources (DERs) as continuous reactive sources in the Preventive control phase is proposed. A simple formula is needed to calculate the extra amount of the reactive power produced by DERs as well as the new voltage at the DERs terminal.

1.2 Unsolvable load flow example

To illustrate the divergent phenomenon, consider the following example.

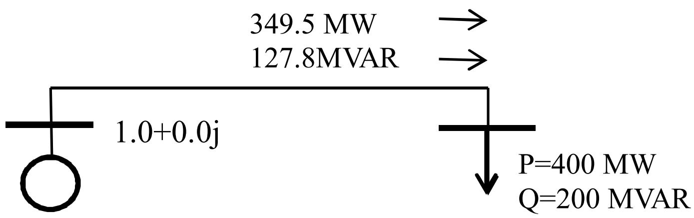


Figure 1: 2-bus network example

Bus 1 is treated as a slack bus with constant voltage of $1.0 + 0.0j$. Bus 2 is a load bus with a constant P-Q demand. For simplicity assume that the transmission line is lossless with reactance of 0.1 per unit and no shunt charging (100 MVA base). The power flow equations for this system are:

$$P = -fB_{12} \quad (1a)$$

$$Q = eB_{12} + f^2B_{22} + e^2B_{22} \quad (1b)$$

With $e + jf$ the phasor voltage at bus 2, $P + jQ$ the demand at the load bus and $B_{12} = 10 = -B_{22}$ the elements of the network bus admittance matrix. The Jacobian of (10) is

$$J = \begin{bmatrix} 0 & -B_{12} \\ B_{12} + 2eB_{22} & 2fB_{22} \end{bmatrix}$$

Depending upon the values of P and Q, (1) can have either two, one or no real solutions [8]. Figure 2 shows these regions in load power parameter space, with the power flow solvable region having two solutions and the unsolvable region having no solution. As was shown in Figure 2, these two regions are separated by a hyper-surface Σ on which the equations have a single solution; for all points on Z the Jacobian of (1) is singular. Thus point a with a P/Q load of 200 + j100 MVA is well within the solvable region, while b with a load of 300 + l50 MVA is close to the boundary but still solvable, while c with a load of 400 + j200 MVA is unsolvable. For this simple example Σ can be determined analytically, be noting it is the set of all points where the Jacobian is singular, or equivalently where the determinant of J is zero:

$$\det(J) = B_{12}(B_{12} + 2eB_{22}) = 0 \qquad (2)$$

Here, where $B_{12} = -B_{22}$, the solution of (2) is $e = 0.5$. Substituting this solution for e into (1b) and using (1a) to solve for the f component of the bus 2 voltage, one gets Σ to be the set of all points where

$$\frac{P^2}{B_{12}} + Q - \frac{1}{4}B_{12} = 0 \qquad (3)$$

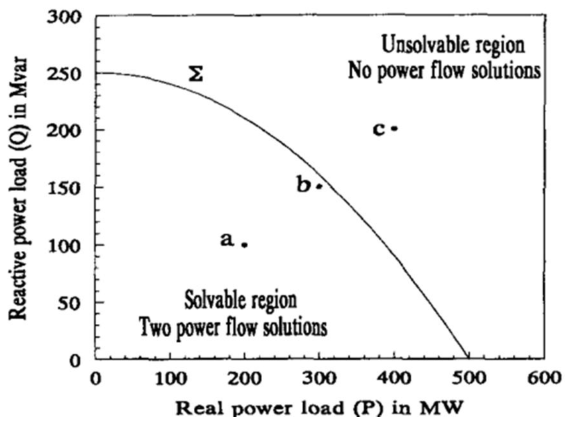


Figure 2: Solvable and unsolvable regions in parameter space

1.3 Motivations

In recent times, Korean power system operating conditions have gradually approached an upper limit because transmission power has been increased, while economic and environmental problems have prevented the transmission system from expanding [30]. Moreover, when a contingency occurs, the power system may have unsolvable cases for which a power flow solution does not exist. These situations mainly occur when the reactive power supplies of the power system do not meet the requirements of the system. Therefore, an adequate plan for either expanding the transmission system or creating reactive power compensation must be established in order for the power system to resolve the undesirable situation.

Security assessments of the power system reflecting the various contingencies must be performed in terms of system operation planning in order to guarantee secure system operations. However, when the system does not have a power flow solution after a contingency, security assessments cannot be performed because the assessments are based on the idea that the power system always has a power flow solution. Hence, a correcting action for the recovery of the power system is required after severe outages in order for the power system to be analyzed in a steady-state condition. In [9-10], Overbye presented a method for determining system controls in order to restore the power flow based on a damped N-R power flow algorithm and a sensitivity analysis [11-12]. Van Cutsem proposed an approach of corrective control implemented by a fast voltage stability simulator using the minimum unrestored load and sensitivity [13]. Granville et al. adopted the direct interior point method in an optimal power flow in order to calculate the minimum load shedding to restore the power flow [14]. Feng et al. in [15] described a method for determining the minimum load shedding required finding the equilibrium point associated with the post-contingency boundary. An effective direction for load shedding was found with a normal vector. The method of shedding load, indeed, has some advantages like effective implementation in a large scale, ability to find the “optimal” direction to curtail the load and there are small errors in estimation [10].

However, by using load shedding for restoration, the system must experience blackouts even if the area is relatively small. Moreover, large errors in estimation can be lessened by applying a better linearizing method which is able to capture high non-linear factors. This thesis outlines a framework for determining the necessary reactive power compensation, instead of load shedding, to restore the power system.

1.4 Problem statement

1.4.1 Causes of load flow divergence and methods of controlling divergence

As is known to most planning and operations engineers, there are often contingent (or sometimes base-case) situations where the N-R power flow does not converge to a solution. Divergence can occur when solving the load flow equations for a variety of reasons:

• Unsolvability, i.e., no solution to the load flow equations exists

• The system solution is too close to the boundary of unsolvability

• The initial guess of the solution is too far from the actual solution

Unsolvability has become more of a problem in the electricity grid since restructuring occurred. This is due to the increased utilization of existing transmission resources without any significant increase in transmission investment. These activities have led to a system that is operated very close to the region of unsolvability, defined as the set of system parameters such that the power flow does not have a solution. When contingency analysis is performed on systems that are already very close to the unsolvability boundary, it is not uncommon to find system configurations that are unsolvable. In fact, there are two strategies following which the operation point can move out of solvable region. One case is due to contingences, the solvable region shrinks and the current operating point is in unsolvable region. The other case is the demands increase and exceed the solvable boundary.

The problem of having a solution that is too close to the boundary of unsolvability is due to the near-singularity of the Jacobian used in the N-R load flow. This problem is particularly prevalent when performing maximum loadability studies. Several techniques have been developed for the sole purpose of avoiding difficulties at the boundary of infeasibility with the standard N-R load flow, most notably the continuation load flow methods.

However, even the continuation methods can have difficulties when the initial guess at a solution is too far from the actual solution. In particular, when the predicted point taken as a result of the predictor step is too far from the solution, the corrector step (load flow solution) may be too far from the solution point, leading to divergence.

The problem of the initial guess has always plagued the N-R method and is one of its primary disadvantages. While the N-R method of solving nonlinear equations is well-established to exhibit quadratic convergence in a region that is sufficiently close to the final solution, the behavior of the N-R load flow when the initial guess is far away from the solution is very unpredictable. In fact, it has been shown that the load flow problem has fractal regions of convergence. The problem of the initial guess can be reduced by the use of scaling factors such as the optimal multiplier [31], or heuristic techniques that prevent power flow divergence by guaranteeing that the sum of the squares of the power flow mismatches decrease with each of iteration [9].

1.4.2 Power flow security regions

As power systems become more heavily loaded, there will be an increase in the number of situations where the power flow equations have no real solution, particularly in contingency analysis and planning applications. Since these cases can represent the most severe threats to viable system operation, it is important that a computationally efficient technique be developed to both quantify the degree of unsolvability, and to provide optimal recommendations of the parameters to change to return to a solvable solution [9].

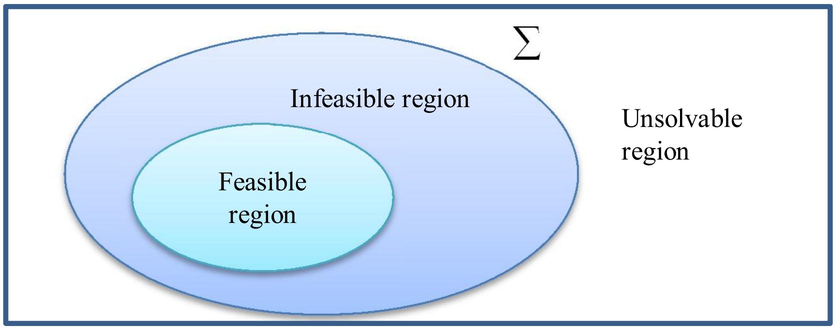


Figure 3: Power flow security regions

The solution of the power flow problem has received much attention over the last several decades. This is due to its fundamental importance to power system analysis. However little attention has been focused on how to handle situations where the power flow equations have no real solution. Intuitively the problem can be illustrated using the well-established concept of security regions [18], [19], [20]. Figure 3 defines three regions in a multi-dimensional parameter space, where the parameters could be bus loads, generator MW injections and voltage set-points, MW interchange levels, etc. Let the feasible region be the set of points where the power flow equations have a solution and all system values (e.g. line flows, bus voltages) are within their limits. Normally this is the desired operating region for the system. Let the infeasible region be the set of points where the power flow equations have a solution, but where one or more limit is violated. Usually it is possible to operate the system (at least for a while) in this region. Much progress has been made in the development of security enhancement tools to provide controller recommendations for moving from the infeasible region back into the feasible region. An example would be the linear programming based optimal power flow [21], [22]. Denote the feasible and infeasible regions as the power flow solvable region. Lastly, let the unsolvable region be the set of points where the power flow equations have no real solution, with the boundary between the unsolvable and solvable regions denoted by Σ .

1.4.2 Methodology for restoration of load flow solvability

For the cases of bad initial guess and the solution is too close to the unsolvable boundary, numerical methods such as optimal multiplier [31] or continuation power flow [32] can be applied. However, for the unsolvable case, the only way to restore solvability would be structure modifications. This methodology uses linearizing techniques and least square minimization to reduce power flow mismatch by controlling switched shunts. As a result, the feasible boundary is enlarged to cover the operation point and power flow problem is solved.

The proposed method for restoring solvability is the first phase of a two-phase security program so-called Corrective and Preventive Control. If a severe contingency that results in an unsolvable case occurs at the system operating point O, the corrective control of compensating reactive power should be promptly carried out to bring the system to solvability by enlarging solvable boundary to cover the point O ($\sum \rightarrow \sum'$). Afterward, if voltages violate constraints, i.e. exceed the desired range, preventive control will be taken place to eliminate all violations by using other security tools. The process is shown in Figure 4.

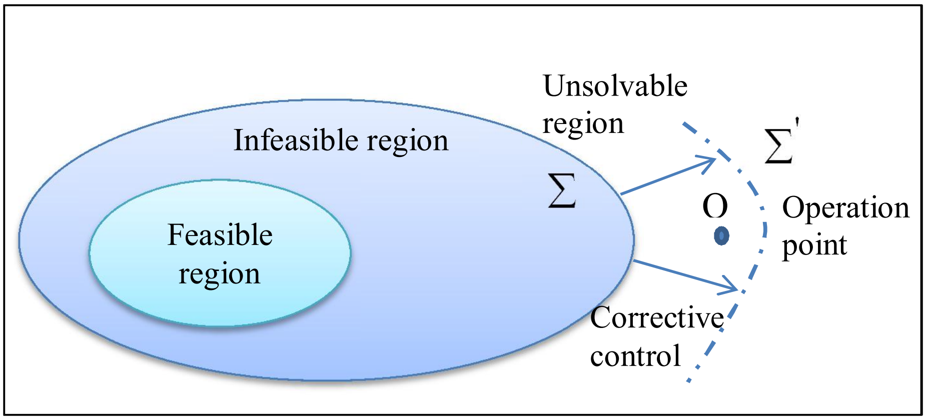
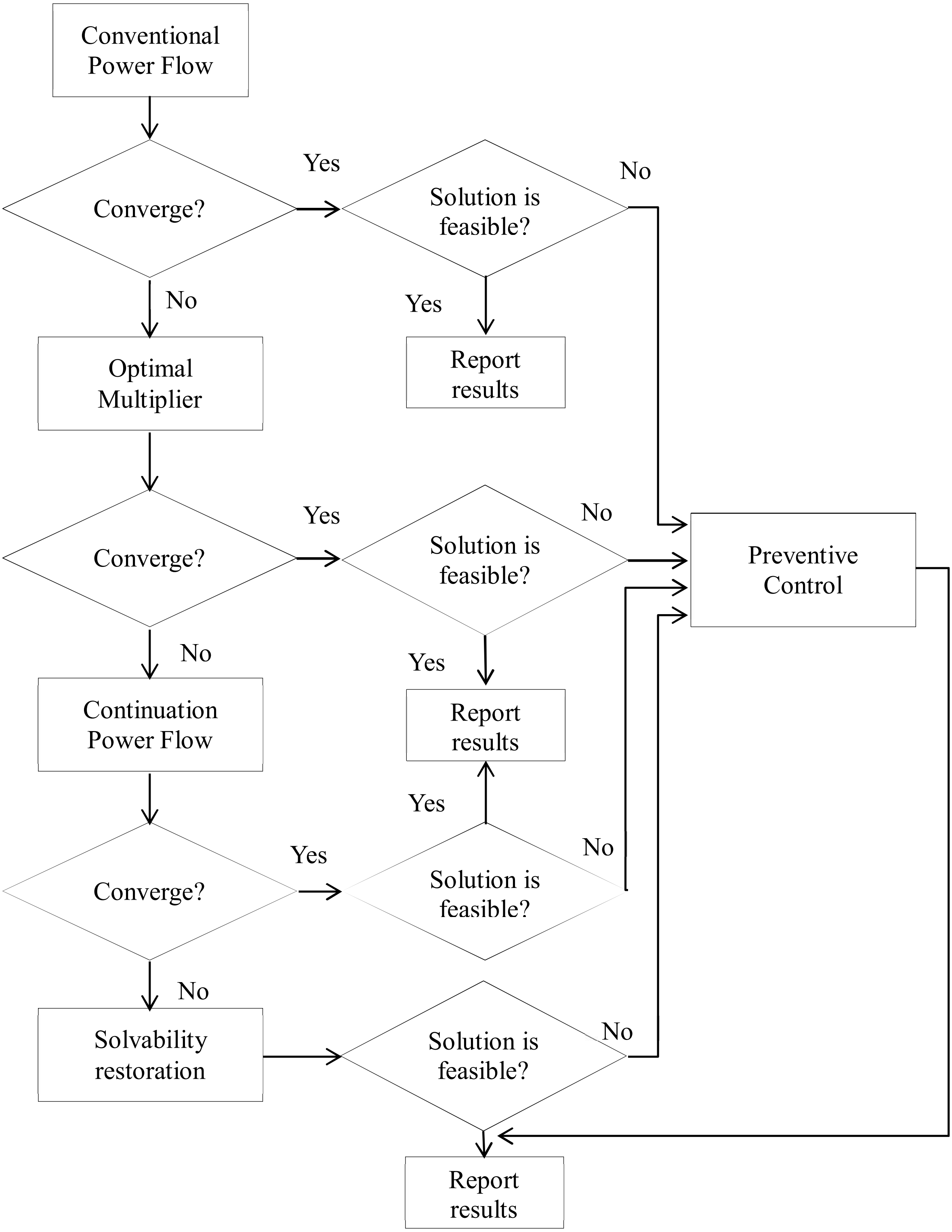


Figure 4: Security regions under the proposed scheme

A detail description is given in the following flow chart.



Flow chart: The Corrective – Preventive control algorithm

1.4.3 Goals of the thesis

This thesis examines in detail the method of solvability restoration for power flow problem. The proposed method is proved to be very powerful, flexible and able to deal with the problem of divergence in a large and high non-linear system.

Furthermore, based on the performance of the proposed method, the perspective of feasible boundary can be switched as follows: instead of shedding load to restore solvability, feasible boundary is extended to cover the load conditions by changing the reactive power compensation, therefore, a new boundary is defined as the maximum of system correcting ability.

1.5 Outline of the thesis

Chapter 2: Power flow solvability restoration (Corrective control)

This chapter describes the power flow solvability restoration method. The linearizing method using the PTDFs concept is presented. The concept of Sphere of Influence is also introduced. Afterward, the relationship between switched shunts changes and the mismatch vector is derived then least square minimization is applied to minimize the mismatch. Moreover, the proposed method is criticized and compared to previous studies.

Chapter 3: Steady state voltage control in integrated DERs networks (Preventive control)

In this chapter, an approach to derive a simple formula to control voltage at some heavy load bus is presented. The reactive power source used in this research is the distributed generator which is adjacent to the heavy load. A new value of voltage at the distributed generator terminal is computed in terms of the voltage deviation of load buses.

Chapter 4: Study Cases

For illustrating how the proposed method can be applied, the tested case is a planning file based on the peak load profile in 2008 in Korea. The file is received from Korea Electric Power Corporation (KEPCO) includes 1336 buses with 1247 load buses and 338 switched shunts buses. Due to inappropriate assignment of switched shunts, power flow solved by N-R method diverges.

The IEEE 118-bus test system then is tested for voltage control purpose. The DER is placed near the low voltage load bus and the terminal voltage of DER is regulated in order to raise the voltage at the bus of interest.

Chapter 5: Conclusions and future works

This is the conclusion chapter. It includes a summary of the work presented in the thesis as well as recommendations for the future works.

Chapter 2

Power flow solvability restoration (Corrective control)

2.1 Conditions for solutions exist

In [16], A. N. Wilson considered the solution of the equation:

$$Ax + F(x) = b \tag{4}$$

where $x = \begin{bmatrix} x_1 \\ \dots \\ x_n \end{bmatrix}$ is a point in the n-dimensional Euclidean space E^n,

$F(x) = \begin{bmatrix} f_1(x_1) \\ \dots \\ f_n(x_n) \end{bmatrix}$ is a nonlinear function mapping E^n into E^n, A is an $n \times n$

matrix of real numbers, and $b = \begin{bmatrix} b_1 \\ \dots \\ b_n \end{bmatrix}$ is an arbitrary point in E^n. It is proved

that there is a unique solution of (4) if:

- Each f_i is a strictly monotone increasing function mapping E^1 onto E^1 and
- The elements a_{ij} of the matrix A satisfy the inequality

$$a_{ij} \geq \sum_{\substack{j=1 \\ j \neq i}}^{n} \left| a_{ij} \right|, \text{ for } i = 1, \dots, n.$$

- Either all of the functions f_i are convex, or else all f_i are concave, and

  $a_{ij} \le 0$ if $i \ne j$

  are sufficient to guarantee that the iterations converge to the solution.

Equations of type (4) occur often in the study of nonlinear electrical networks. Based on above idea, in [17], J Thorp, D Schuzl and M Ilic presented the conditions for existence of solution and localized disturbance propagation in reactive power-voltage problem.

Consider a lossless electric power system with the load (P-Q) buses numbered 1, 2 ..., n and the generator (P-V) buses numbered n + l, n + 2 ..., n +K. The reactive power balance equation at each load bus can be written as:

$$\left[\sum_{j \ne i} B_{ij} - b_i\right] v_i^2 - \sum_{\substack{j=1 \\ j \ne i}}^{n+K} B_{ij} \cos\theta_{ij} v_i v_j - Q_i = 0 \tag{5}$$

Starting with (5), add and subtract $\lambda_i v_i^2$, divided by v_i and put all terms involving generator voltages on the-right hand side to get:

$$[B_{ii} - b_i - \lambda_i] v_i - \sum_{\substack{j=1 \\ j \ne i}}^{n} B_{ij} \cos\theta_{ij} v_i v_j + \lambda_i v_i - \frac{Q_i}{v_i} = \sum_{j=n+1}^{n+K} B_{ij} \cos\theta_{ij} v_i v_j \tag{6}$$

or, put in matrix form,

$$(\tilde{G} - \Lambda) x + f(x) = c \tag{7}$$

where Λ is a diagonal matrix with the ith diagonal entry equal to λ_i. We note that since $B_{ij} \ge 0$, $v_i > 0$, $-\pi/2 < \theta_{ij} < \pi/2$, we have $c \ge 0$. The function

$f(x)$ has the form $\left[f_1(x_1) \quad \ldots \quad f_n(x_n)\right]^T$ where $f_i(x_i) = \lambda_i x_i - Q_i / x_i$. Hence, if the load at node i is capacitive, Q_i will be positive, and $f_i(x_i)$ will be monotonically increasing for all $x_i > 0$ and have a zero at $(Q_i / \lambda_i)^{1/2}$. If the load at node i is inductive, Q_i will be negative, and from

$$\frac{d(f_i(x_i))}{x_i} = \lambda_i + Q_i / x_i^2$$

we see that $f_i(x_i)$ has a minimum at $x_i = (Q_i / \lambda_i)^{1/2}$ and is monotonically increasing for $x_i > (Q_i / \lambda_i)^{1/2}$.

The function f_i for Q_i positive and negative are shown in Figure 5.

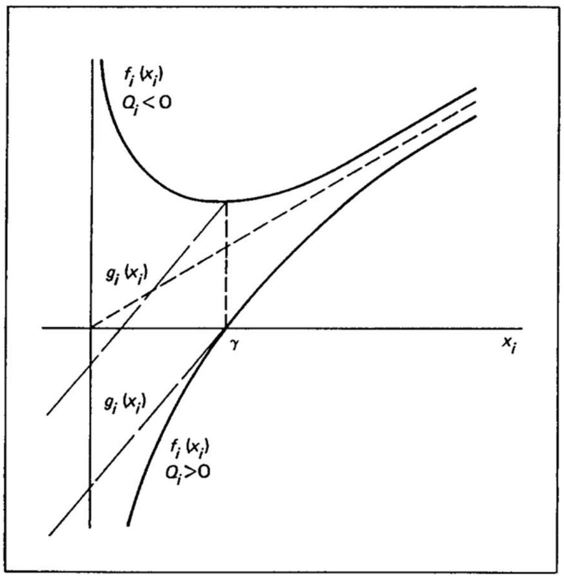


Figure 5: Nonlinearities in Q-V decoupled load flow

Let $\hat{\lambda} = \max_i \lambda_i$, $\tilde{\lambda} = \hat{\lambda} - \lambda_i$ and let $\tilde{\Lambda}$ be the diagonal matrix with the ith diagonal entry given by $\tilde{\lambda}_i$. Then we can write $\left[\tilde{G}-\Lambda\right]=\left[\tilde{G}+\tilde{\Lambda}-\hat{\lambda}I\right]$. It is assumed that $\left[\tilde{G}+\tilde{\Lambda}\right]$ have a positive inverse. Letting $G=\tilde{G}+\tilde{\Lambda}$ we can write:

$$\left[\tilde{G}-\Lambda\right]=\left[\tilde{G}+\tilde{\Lambda}-\hat{\lambda}I\right]=\left[G-\hat{\lambda}I\right] \tag{8}$$

Let $\lambda_i=|Q_i|/\gamma^2$ and define

$$g_i(x_i)=\begin{cases} f_i(x_i) & x_i\ge\gamma \\ (x_i-\gamma)+\dfrac{|Q_i|-Q_i}{\gamma} & x_i<\gamma \end{cases}$$

Then we see that $g(x)$ maps R^n onto R^n, is monotonically increasing for all x, coincides with $f(x)$ for $x\ge\gamma$, and $g(x)>0$ for $x>\gamma$. The function $g_i(x_i)$ is shown in Figure 5 for Q_i positive and negative. From this point on, $\gamma=0.8$ per unit is used, as 0.8 is a reasonable lower limit on the voltage magnitudes of interest. The results of Willson [16] can be used to find out the conditions which guarantee that is has a unique solution with $x_i>\gamma$ as following:

Theorem:

If $\max_i|Q_i|<\frac{1}{2}\gamma^2\lambda_{\min}[G]$ (9) there is an α^* such that (7) has a unique solution with a load bus voltage magnitudes greater than γ if the source voltages are all greater than α^*.

The above theorem explains the phenomenon of non-existing solutions in power systems due to the consumption increases. Under a heavy load condition, voltages prone to decrease, as a result the lower limit of voltage γ shrinks. Thereby, the condition (9) no longer holds then the desired solution does not exist. To tackle with this problem, it is necessary to control reactive powers in such a way that the voltage profile can be improved. Indeed, if voltages increase, not only γ but also $\lambda_{\min}\left[G\right]$ will increases since matrix $\left[G\right]$ becomes more “dominant”.

2.2 Solvability restoration

2.2.1 The origin of the idea

In [9], Overbye pointed out that the system can be moved back to the solvable region boundary if the power injections are changed so all bus mismatches are set to zero. However, instead of changing power injections, if we can compensate reactive power such that minimizing the mismatch, power flow will converge or the operation point will be in solvable region.

Furthermore, appropriate reactive power compensation will support the voltage profile then the lower limit of voltages increases which ensures the solution exists [17].

2.2.2 PTDFs

For the case of divergence, mismatch of N-R method tends to increase over iterations, so the computation loop never terminates. The proposed idea is to tackle the problem of divergence by finding ways to reduce this mismatch. In this thesis, the relationship between the changes of switched shunts and the mismatch is built. The concept of Power Transfer Distribution Factors (PTDFs) is useful for linearizing the network which can be used to derive some simple relationships.

The reactive power flows through the line l_{ij} between bus i and bus j can be computed as:

$$Q_{l(ij)} = -V_i^2 \cdot B_{ij} - V_i \cdot V_j \cdot [G_{ij} \cdot \sin(\delta_i - \delta_j) - B_{ij} \cdot \cos(\delta_i - \delta_j)] \qquad (10)$$

where V_i, δ_i and V_j, δ_j are the voltage magnitudes and angles of bus i and bus j, respectively; G_{ij} and B_{ij} is the conductance and the susceptance of line l_{ij}, respectively. If G_{ij} and ($\delta_i - \delta_j$) can be neglected, the above formula becomes:

$$Q_{l(ij)} \approx -B_l (V_i^2 - V_i V_j \cos\delta_{ij}) \qquad (11)$$

Now PTDF of the reactive power through the line l_{ij} with respect to the reactive power of load bus k is obtained as:

$$\begin{aligned} p_{ij-k} &= \frac{dQ_{l(ij)}}{dQ_k} = -B_{ij} . \frac{d}{dQ_k} (V_i^2 - V_i V_j \cos\delta_{ij}) \\ &= -B_{ij} . V_i \frac{2}{\frac{\partial Q_k}{\partial V_i}} + B_{ij} (V_j \cos\delta_{ij} \frac{1}{\frac{\partial Q_k}{\partial V_i}} + V_i \cos\delta_{ij} \frac{1}{\frac{\partial Q_k}{\partial V_j}} - V_i V_j \sin\delta_{ij} (\frac{1}{\frac{\partial Q_k}{\partial \delta_i}} - \frac{1}{\frac{\partial Q_k}{\partial \delta_j}})) \\ &= -B_{ij} . (2V_i - V_j \cos\delta_{ij}) \frac{1}{\frac{\partial Q_k}{\partial V_i}} + B_{ij} V_i (\frac{\cos\delta_{ij}}{\frac{\partial Q_k}{\partial V_j}} - V_j \sin\delta_{ij} (\frac{1}{\frac{\partial Q_k}{\partial \delta_i}} - \frac{1}{\frac{\partial Q_k}{\partial \delta_j}})) \end{aligned} \qquad (12)$$

where Q_k is the reactive power of load bus k.

2.2.3 Sphere of influence

The tier approach is an efficacious structure organization of the electric power system network used for simplifying the computation process with minor errors. As shown in Figure 6, the considered bus where a switched shunt (SS) resides is defined as the center bus. All load buses directly link to the centric bus are in the first tier. Subsequent tiers include load buses which are directly link to the load buses in previous tier. Since SS control affects the network only locally [23-24], there exists a positive integer N such as voltages of load buses in tier N+1 are not affected by the centric bus control. Therefore, tier N is the fringe one. Practically, if load buses voltage deviations in tier N+1 are less than 10% of the voltage deviation at centric bus, tier N+1 could be considered as an un-impregnated stratum. Sphere of influence (SOI) of the centric bus is defined as the subset includes all load buses participate in from the first tier to the fringe. Voltages at others buses which do not belong to SOI will be fixed when centric bus controls voltage.

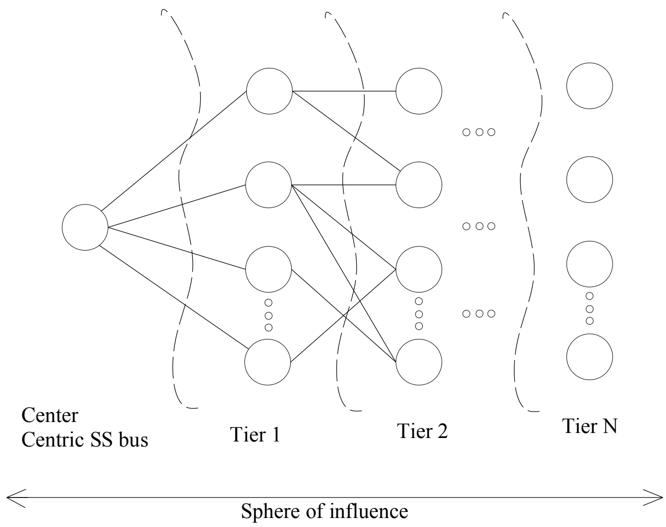


Figure 6: The sphere of influence

[25] presented Electrical Distance based method developed by Electricite de France (EDF). The different physical variables of a meshed electrical system are linked by the matrix equations presented below:

$$[\Delta I]=[Y_{bus}][\Delta V] \qquad [\Delta Q]=[\partial Q/\partial V][\Delta V]$$

$$[\Delta V]=[Z_{bus}][\Delta I] \qquad [\Delta V]=[\partial V/\partial Q][\Delta Q]$$

The matrix $[Y_{bus}]$ is the matrix of admittances. The matrix $[Z_{bus}]$ is the matrix of impedances. Both matrices are the inverse of each other, complex and symmetrical. The matrix $[\partial Q/\partial V]$ is part of the Jacobian matrix which appears during a load-flow computation following the N-R method. Its inverse $[\partial V/\partial Q]$ is called sensitivity matrix. These are real and non-symmetrical matrices. The matrices $[Y_{bus}]$ and $[\partial Q/\partial V]$ are sparse matrices whose non-zero elements correspond to the connection lines between electrical substations. In each node they verify that $\sum I = 0$ and $\sum Q = 0$. The matrices $[Z_{bus}]$ and $[\partial V / \partial Q]$ are full matrices whose elements reflect the propagation of the voltage variations following a current or reactive power injection in a given node throughout the system.

The last two matrices are taken to quantify proximities in terms of voltage. The magnitude of the coupling in terms of voltage between two nodes of an electrical system can be reflected and quantified by the maximum attenuation of voltage variations between these two nodes. These attenuations are easy to obtain from the matrix $[\partial V / \partial Q]$. To do so, one just needs to divide the elements of each column by the diagonal term. For matrix $[Z_{bus}]$, the resistive terms (real part) compared to the inductances and the capacitances (imaginary part) can be neglected, and one then proceeds in the same way. In practice, the matrix $[\partial V / \partial Q]$ which takes both active and reactive power flows into account is used rather than $[Z_{bus}]$, but this implies implicitly uncoupling of active and reactive power problems.

A matrix of attenuations between all the nodes of system, whose terms are written a_{ij}, is then available. We have:

$$\Delta V_i = \alpha_{ij} \Delta V_j \text{, with } \alpha_{ij} = \left[\frac{\partial V_i}{\partial Q_j}\right] / \left[\frac{\partial V_j}{\partial Q_j}\right]$$

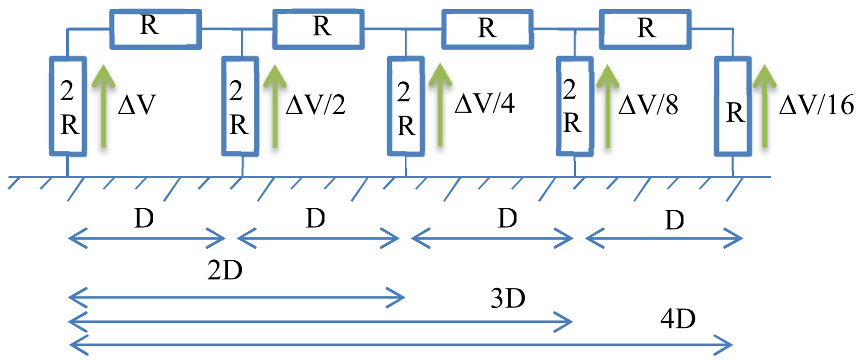


Figure 7: The attenuations on a simple example

However, for efficient application of certain algorithms or heuristic methods, the data are most easy manipulated if a mathematical structure of distance between all the nodes can be defined. Taking a simple system (such as that in Figure 7), it is necessary to effect the product of attenuations to change over from a couple of nodes to another. To switch over from a product to a sum, it is possible to take the logarithm of attenuation as definition of the distance between two nodes.

$$D_{ij} = -Log(\alpha_{ij})$$

However, to obtain symmetrical distances, the formulation below is taken as definition of the electrical distance between two nodes i and j:

$$D_{ij} = D_{ji} = -Log(\alpha_{ij} \ . \ \alpha_{ji})$$

This function D_{ij} has the properties of positivity, symmetry, and it can be shown that if the system is not over-compensated, i.e. the capacitors only attenuate the dominant inductive terms without eliminating them then the triangular inequality is also verified: the electrical distances are real mathematical distances.

The electrical distances once specified can be used to determine the zones and pilot nodes of the secondary voltage control. The objective is to group voltage generators into homogeneous zones. Typological analysis methods are used to this end. The aim of typological analysis is to simplify a complex reality by forming a class of similar objects or individuals. Thereby, the network is divided in a number of geographic regions. One or a few so-called pilot nodes, which are assumed to be representative of the voltage situation in the region, are selected for voltage regulation by the secondary controller. The main actuators are the set-point voltages of the primary controllers of the generators within a region, although the French implementation also uses static compensation devices such as capacitor banks and reactors. The set-point values are calculated by an optimization procedure using a linearized static network model to make each generator in the region contribute to the control of the pilot node voltage(s). This optimization takes the individual generators' control authority and equipment limits into account. Furthermore, each region is assumed to be independent.

Although secondary (regional) voltage control based on the electrical distances concept developed by EDF is widely accepted and has been implemented in some European systems, for example in France [26] and Italy [27], this approach generally is not suited to North American electric power grids, where the network tends to be tightly coupled. As the system loads increase, the interactions between power system components also become more significant [28]. Therefore, the components of $\cos(\delta_i - \delta_j)$ cannot be replaced by 1, the network in fact, becomes a high nonlinear one. We have proposed a new approach for determining the electrical distances on the foundation of PTDFs, taking account of the high nonlinear components, which pertaining to the network where no solution exists due to heavy loads, and dependence on state of the network.

TABLE I

Comparison between the two Methods of Determining Electrical Distances

	Developed by EDF	The proposed method
Advantages	▪ Simple • Only consider network structure ▪ Visualize how reactive powers loss through transmission lines	▪ Elaborated
Disadvantages	▪ Existing flaws • Ignore the dependence on state of the system	▪ Successfully address the relationship with system properties and system state

2.2.4 Linearizing the network

If the switched shunt resides at bus i (center), we define Ω_1, Ω_N as:

$\Omega_1 = \Omega(\text{E1}) = \{\text{j} \mid \text{bus j} \in \text{tier 1}\}$; $\aleph(\Omega_1) = n_1$

$\Omega_N = \Omega(\text{SOI}) = \{\text{k} \mid \text{bus k} \in \text{SOI}\}$; $\aleph(\Omega_N) = n_N$

where $\aleph(\cdot)$ is the cardinality of a set. Obviously, Ω_1 belongs to Ω_N. Then the table of p_{ij} is constructed as:

TABLE II

Power Transfer Distributed Factors

Line / Load	ij	i(j+1)	...
k	p_{ij-k}	$p_{i(j+1)-k}$	...
k+1	$p_{ij-(k+1)}$	$p_{i(j+1)-(k+1)}$	...
...	...	...	...

where $j \in \Omega_1$; $k \in \Omega_N$

The reactive power deviation of each line can be computed as:

$$\Delta Q_{l(ij)} = \sum_{j \in \Omega_1, k \in \Omega_N} \frac{dQ_{l(ij)}}{dQ_k} \Delta Q_k \tag{13}$$

Let $p_{ij-k} = \dfrac{dQ_{l(ij)}}{dQ_k}$ then

$$\Delta Q_{l(ij)} = \sum_{j \in \Omega_1, k \in \Omega_N} p_{ij-k} \Delta Q_k \tag{14}$$

where $\Delta Q_{l(ij)}$ and ΔQ_{Lk} are the reactive power deviation of line l_{ij} and the load at bus k. The mismatch of reactive power at bus i where switched shunt (SS) resides can be represented in terms of lines reactive power deviation:

$$\Delta Q_i = \sum_{j \in \Omega_1} \Delta Q_{l(ij)} \tag{15}$$

In matrix form it becomes:

$$\Delta Q_i = \left[p^i \right] \left[\Delta Q_k \right] \tag{16}$$

where

$$\left[p^i \right] = [p^i_j \quad \dots \quad p^i_k \quad \dots \quad p^i_{j+n_N-1}] \in R^{1 \ x \ n_N}$$

$$p^i_k = \sum_{j \in \Omega_1} p_{ij-k} ; k \in \Omega_N$$

$$\left[\Delta Q_k \right] = [\Delta Q_j \quad \dots \quad \Delta Q_k \quad \dots \quad \Delta Q_{j+n_N-1}]^T \in R^{n_N x \ 1}$$

Or in another way:

$$\Delta Q_i = \begin{bmatrix} 0 & p^i_j & \dots & p^i_k & \dots & p^i_{j+n_N-1} \end{bmatrix} \begin{bmatrix} \Delta Q_i \\ \Delta Q_j \\ \dots \\ \Delta Q_{j+n_N-1} \end{bmatrix} \tag{17}$$

Similarly, these following expressions are derived:

$$\Delta Q_j = \begin{bmatrix} p^j_i & 0 & \dots & p^j_k & \dots & p^j_{j+n_N-1} \end{bmatrix} \begin{bmatrix} \Delta Q_i \\ \Delta Q_j \\ \dots \\ \Delta Q_{j+n_N-1} \end{bmatrix} \tag{18}$$

$$\dots$$

$$\Delta Q_{j+n_N-1} = \begin{bmatrix} p^{j+n_N-1}_i & p^{j+n_N-1}_j & \dots & p^{j+n_N-1}_k & \dots & 0 \end{bmatrix} \begin{bmatrix} \Delta Q_i \\ \Delta Q_j \\ \dots \\ \Delta Q_{j+n_N-1} \end{bmatrix}$$

Solving the set of n_N above equations we get:

$$-\begin{bmatrix} p_i^j \\ \dots \\ p_i^k \\ \dots \\ p_i^{j+n_N-1} \end{bmatrix} * \Delta Q_i = \begin{bmatrix} -1 & \dots & p_k^i & \dots & p_{j+n_N-1}^i \\ \dots & \dots & \dots & \dots & \dots \\ p_j^k & \dots & -1 & \dots & p_{j+n_N-1}^k \\ \dots & \dots & \dots & \dots & \dots \\ p_j^{j+n_N-1} & \dots & p_k^{j+n_N-1} & \dots & -1 \end{bmatrix} \begin{bmatrix} \Delta Q_j \\ \dots \\ \Delta Q_k \\ \dots \\ \Delta Q_{j+n_N-1} \end{bmatrix} \quad (19)$$

Or

$$-N * \Delta Q_i = M * \begin{bmatrix} \Delta Q_j \\ \dots \\ \Delta Q_k \\ \dots \\ \Delta Q_{j+ni-1} \end{bmatrix} \quad (20)$$

then

$$\begin{bmatrix} \Delta Q_j \\ \dots \\ \Delta Q_k \\ \dots \\ \Delta Q_{j+ni-1} \end{bmatrix} = -M^{-1}N * \Delta Q_i \quad (21)$$

where $-M^{-1}N$ is of the form:

$$-M^{-1}N = U = \left[u\right]_{ni \text{ x } 1} = \begin{bmatrix} u_j \\ \dots \\ u_k \\ \dots \\ u_{j+ni-1} \end{bmatrix} \quad (22)$$

From (14), (21) and (22), we have:

$$\begin{aligned} \Delta Q_{l(ij)} &= \sum_{j\in\Omega_1, k\in\Omega_N} p_{ij-k} u_k \Delta Q_i \\ &= \Delta Q_i \sum_{j\in\Omega_1, k\in\Omega_N} p_{ij-k} u_k = h_{ki} \Delta Q_i \end{aligned} \quad (23)$$

where $h_{ij-i} = \sum_{j \in \Omega_1, k \in \Omega_N} p_{ij-k} u_k$

Let ΔQ_{ss-i} be amount of reactive power change due to SS at bus i then the reactive power transferred from bus i to bus j will vary with amount of ΔQ_{ss-ij} and

$$\Delta Q_{ss-i} = \Delta Q_i$$

$$\Delta Q_{ss-ij} = \Delta Q_{l(ij)}$$

Then $\Delta Q_{ss-ij} = h_{ij-i} \Delta Q_{ss-i}$ (24)

Equation (24) shows that how the reactive power transferred from bus i to bus j varies when SS changes.

2.2.5 Least square minimization

Based on the above tier approach, it is able to divide the network into several Zones according to the group of local switched shunts. Let $[\Delta Q]$ be mismatch vector we derive after some iterations. There are 4 steps to divide the network:

Step 1: Forming Zone 1

- Search the network to find the bus with largest mismatch
- The closest SS bus will be chosen as the centric bus.
- Find the SOI for this center and all load buses in this SOI will be added to Zone 1.

Step 2: Expanding Zone 1

- Each SS bus in Zone 1, in turn, is set as center and all buses belong to its SOI will be added to Zone 1.

Step 3:

Continue expanding Zone 1 until:

- There are no more SS buses in Zone 1 to set as centric bus.

- The number of buses in Zone 1 is more than the limited size of full matrix is able to solve.

Step 4:

Forming Zone 2, Zone 3 with the rest buses until all SS buses are listed in Zones.

For each Zone, its switched shunts are controlled to reduced mismatch of buses inside. For some Zone with n buses and m SS buses with m < n, the mismatch is:

$$\left[\Delta Q\right] = \begin{bmatrix} \Delta Q_i \\ \ldots \\ \Delta Q_j \\ \ldots \\ \Delta Q_{i+n-1} \end{bmatrix} \quad (25)$$

After SS changes, the new mismatch vector is:

$$\left[\Delta Q'\right] = \begin{bmatrix} \Delta Q'_i \\ \ldots \\ \Delta Q'_j \\ \ldots \\ \Delta Q'_{i+n-1} \end{bmatrix} \quad (26)$$

From (15): $\Delta Q_{ss-ij} = h_{ij-i}\Delta Q_{ss-i}$ where $h_{ij} = 0$ if $B_{ij} = 0$. Then

$$\begin{bmatrix} \Delta Q'_i \\ \dots \\ \Delta Q'_j \\ \dots \\ \Delta Q'_{i+n-1} \end{bmatrix} = \begin{bmatrix} \Delta Q_i \\ \dots \\ \Delta Q_j \\ \dots \\ \Delta Q_{i+n-1} \end{bmatrix} + \begin{bmatrix} h_{ii} \\ \dots \\ h_{ji} \\ \dots \\ h_{(i+n-1)i} \end{bmatrix} \Delta Q_{ss-i} + \begin{bmatrix} h_{ij} \\ \dots \\ h_{jj} \\ \dots \\ h_{(i+n-1)j} \end{bmatrix} \Delta Q_{ss-j} + \dots \quad (27)$$

where $h_{ii} = \sum_k h_{ik-i}$; $h_{ji} = \sum_k h_{jk-i}$; $h_{(i+n-1)i} = \sum_k h_{(i+n-1)k-i}$;… bus i, j,… are SS buses.

Equation (27) is rewritten as:

$$\begin{bmatrix} \Delta Q'_i \\ \dots \\ \Delta Q'_j \\ \dots \\ \Delta Q'_{i+n-1} \end{bmatrix}_{nx1} = \begin{bmatrix} \Delta Q_i \\ \dots \\ \Delta Q_j \\ \dots \\ \Delta Q_{i+n-1} \end{bmatrix}_{nx1} + \begin{bmatrix} h_{ii} & \dots & h_{ij} & \dots \\ \dots & \dots & \dots & \dots \\ h_{ji} & \dots & h_{jj} & \dots \\ \dots & \dots & \dots & \dots \\ h_{(i+n-1)i} & \dots & h_{(i+n-1)j} & \dots \end{bmatrix}_{nxm} \begin{bmatrix} \Delta ssQ_i \\ \dots \\ \Delta ssQ_j \\ \dots \\ \\ \end{bmatrix}_{mx1} \quad (28)$$

Or:

$$\Delta' = \Delta + H\Delta ss \quad (29)$$

And we try to minimize $\|\Delta'\|_2$ with respect to the change of SS buses (Δss).

To minimizing mismatch Δ' is a standard Least Square Minimization and the solution is

$$\Delta ss = \left([-H]^T [-H]\right)^{-1} [-H]^T \Delta \quad 30)$$

Based on Δss, SS is controlled to minimize mismatch in the considered Zone. Simply, a negative Δ entry indicates the shortage of reactive power then SS will be controlled to compensate reactive power there. An excess of reactive power is denoted by a positive Δ entry and control actions need to withdraw reactive power.

2.2.6 Comparisons and critiques

As mentioned before, the only way to restore solvability would be structure modifications. Various methods have been proposed to tackle with this problem [9-10], [14-16], [33-34]. These works, in fact, have their own disadvantages, limitations and disadvantages. In 1994-1995, Overbye presented a method for determining system controls in order to restore the power flow based on a damped Newton-Raphson power flow algorithm and a sensitivity analysis [9-10]. This method is able to find out the minimum of the cost function (the closest point on the solvable boundary) and the best direction to shed the loads to restore solvability. Nevertheless, the solution depends on the curvature of the solvable boundary and the errors are minor if the boundary is flat. Another limitation is lack of interaction between voltage control actions. The disadvantage is using load shedding to restore solvability. In 1996, Granville et al. adopted the direct interior point method in an optimal power flow in order to calculate the minimum load shedding to restore the power flow [14]. This method had some advantages like ability to take in account all constraints, combination reactive power control and minimizing load shedding, and overcoming problem of Jacobian matrix singularity with conventional power flow. Howbeit, it consumed time and required a great computational effort due to its complexity and difficulty of dividing the networks. In 1998, Feng et al. described a method for determining the minimum load shedding required to find the equilibrium point associated with the post-contingency boundary [15]. Feng's method could minimize the control actions and identify the most effective control strategy but this also consumes time and the loads must be curtailed. In 2000, Luciano V. Barboza modeled the problem of restoring the solvability of the power flow equations as the minimization of the summation of the squares of the power flow mismatches subject to equality constraints [33]. This method combined simplicity of the steady state network equations and the efficiency of Newton method and required less computational effort. Luciano V. Barboza followed the idea of loads shedding thereby the system partly experienced blackouts. Solvability restoration with reactive power compensation was mentioned in [34] Andre G.C. Conceicao proposed a method included two steps: (i) quantifying the systems unsolvability degree (UD); (ii) determining a corrective control strategy to pull system back to feasible region. This work took in account various voltage controls but it ignores the locally effect of voltage control like switch shunts (SS) controls, only considers the changing of reactive power at the bus where SS resides. Moreover, it took time to search the controls in the network. Finally, in 2011, Sangsoo Seo et al. introduced a methodology using a tool based on the branch-parameter continuation power flow (BCPF) in order to restore the power flow solvability in unsolvable contingencies [30]. This method is able to maintain loads by compensate reactive power. Similar to previous works, it lacks for capturing the locally effect of voltage control. The main drawbacks are that it much depends upon the network configuration and consumes time to search the lines for shipping.

Compared to previous studies, the proposed method has various advantages such as optimizing reactive power compensation, ability to tackle with a large and complex system, maintaining all the demands thereby no blackouts occur, fast and less computational burden. However, there are some existing limitations because this method does not take in account limitations of reactive sources and diversity of voltage control types. It only deals with load flow divergent problem pertaining to reactive power. Moreover, the main disadvantage of the method is that it is difficult to find the “best” iteration to apply the proposed method, therefore it is needed to trade-off between accuracy, time consumption and ability to restoring solvability.

Chapter 3

Steady state voltage control in integrated DERs networks (Preventive control)

3.1. Method for steady state voltage monitoring and control

[23] describes the theoretical and algorithmic enhancements of the method for steady state voltage monitoring and control. The approach in the proposed method is to attempt to maintain a given "optimal" voltage profile as the load demand, generation availability and network topology vary. In mathematical terms, the problem is to minimize, a vector of load voltage deviation only.

3.2. The attenuation factor α based on PTDFs

The desired result the attenuation factor α satisfies:

$$\Delta V_{DER} = \alpha \Delta V_L \tag{31}$$

where ΔV_{DER} and ΔV_L are the variation of voltage at terminal of DER and at the load bus needed to control voltage. From (12) and (13), we have:

$$\begin{bmatrix} \Delta Q_j \\ \dots \\ \Delta Q_k \\ \dots \\ \Delta Q_{j+ni-1} \end{bmatrix} = U * \Delta Q_i \tag{32}$$

By introducing the DER reactive power mismatch $\Delta Q_{DER} = \Delta Q_i$, (32) is rewritten as:

$$\begin{bmatrix} \Delta Q_{DER} \\ \Delta Q_j \\ \cdots \\ \Delta Q_k \\ \cdots \\ \Delta Q_{j+ni-1} \end{bmatrix} = \begin{bmatrix} 1 \\ U \end{bmatrix} * \Delta Q_{DER} \tag{33}$$

The power flow equations can be rewritten as:

$$\left[J_V\right] \begin{bmatrix} \Delta V_{DER} \\ \Delta V_j \\ \cdots \\ \Delta V_k \\ \cdots \\ \Delta V_{j+ni-1} \end{bmatrix} = \begin{bmatrix} \Delta Q_{DER} \\ \Delta Q_j \\ \cdots \\ \Delta Q_k \\ \cdots \\ \Delta Q_{j+ni-1} \end{bmatrix} \tag{34}$$

where $\left[J_V\right]$ is a part of Jacobian matrix corresponding the deviation of voltage and mismatch of reactive power at DER bus and related buses listed in (27). Combining (33) and (34), we derive:

$$\left[J_V\right] \begin{bmatrix} \Delta V_{DER} \\ \Delta V_j \\ \cdots \\ \Delta V_k \\ \cdots \\ \Delta V_{j+ni-1} \end{bmatrix} = \begin{bmatrix} 1 \\ U \end{bmatrix} * \Delta Q_{DER} \tag{35}$$

Then

$$\begin{bmatrix} \Delta V_{DER} \\ \Delta V_j \\ \cdots \\ \Delta V_k \\ \cdots \\ \Delta V_{j+ni-1} \end{bmatrix} = \left[J_V\right]^{-1} \begin{bmatrix} 1 \\ U \end{bmatrix} * \Delta Q_{DER} \tag{36}$$

Let

$$\left[J_V\right]^{-1}\begin{bmatrix}1\\U\end{bmatrix} = D = \begin{bmatrix}d_{DER}\\d_j\\\cdots\\d_k\\\cdots\\d_{j+ni-1}\end{bmatrix} \tag{37}$$

Assume that bus j is the bus with low voltage, i. e $V_j < 0.95$. We need to raise its voltage equals 0.95. To do that, the DER will increase the terminal voltage as

$$\Delta V_{DER} = \frac{d_{DER}}{d_j}(0.95 - V_j) = \alpha \Delta V_j \tag{38}$$

$$\alpha = \frac{d_{DER}}{d_j} \tag{39}$$

Obviously, the value of α can be used to quantify the electrical distances as mentioned in the part of 2.2.3, Chapter 2. Since the PTDFs computation takes in account the high non-linear components, this approach gives more precise results compared to one developed by EDF.

Preventive control is a promising method for steady state voltage control because of its simplicity and good approximations which turn out precise results. Nevertheless, it is still limited due to lack of voltage control coordination and requiring DERs ubiquity. As a matter of fact, the proposed method much depends on voltage control ability of DERs.

Chapter 4

Study Cases

4.1. Solvability restoration: Korean case

In this section, a test case is presented: this test case built based on the peak load profile of 2008 in Korea by Korea Electric Power Corporation (KEPCO). This test case includes 1336 buses with 1247 load buses and 338 switched shunts buses.

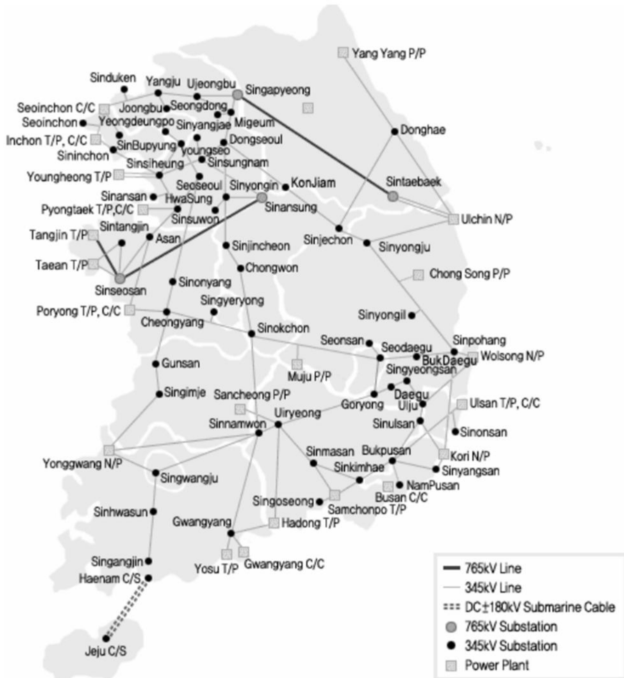


Figure 8: Transmission diagram of the Korean power system

Due to high reactive demands and inappropriate allocation of switched shunts, the system has no solutions as a result power flow solved by N-R method diverges.

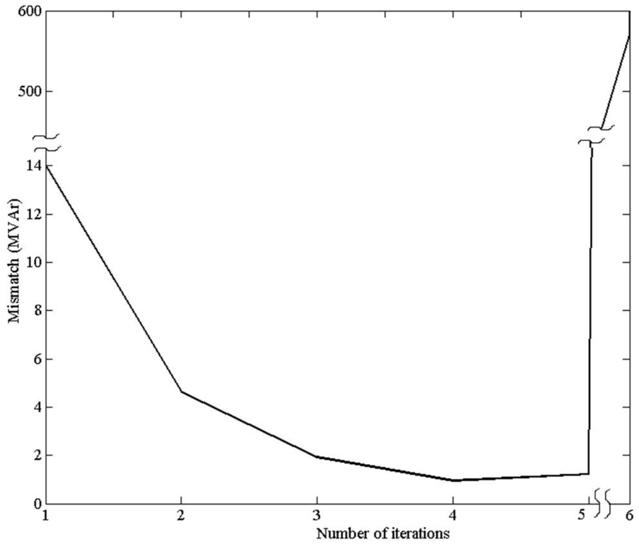


Figure 9: Convergence characteristic of original problem

After the first six iterations, mismatch dramatically increases to 10^7 MVAR, and power flow starts to diverge. The proposed method showed a good performance dealing with the divergence problem.

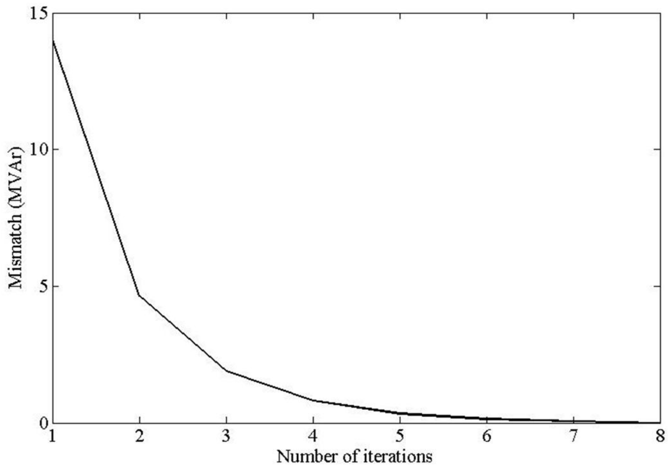


Figure 10: Convergence characteristic of PF with controlled SS

By applying the new method, mismatch obviously decreases and finally, power flow converges.

4.2. Steady state voltage control

The control method has been tested for the IEEE 118-bus system to demonstrate its effect. In which, load bus #118 has a low voltage of 0.94741 and the DER resides at bus #76. The target of the program is controlling the terminal voltage of the DER to raise the voltage at bus #118 to $V_{desired} = 0.95$ based on information of the coefficient α .

With $\alpha_{118} = 0.5790$, $\Delta V_{118} = 0.00259$, the DER must be set a new terminal voltage: $V'_{DER} = V_{DER} + \alpha_{118}.\Delta V_{118} = 0.9582$. From the results shown in Table 3, the new voltage at DER bus #76 is 0.9582 and the voltage at the load bus #118 is improved and equals to $V_{desired} = 0.95$

TABLE III

Results of Power Flow with DER Control

BUS#	**NAME**	**BASKV**	**VOLT**		**ANGLE**	**ALPHA**
			Before control	After control		
38	BUS-38	100	0.96188	0.96189	17.1	0.001
45	BUS-45	100	0.98675	0.98676	15.8	0.001
75	BUS-75	100	0.96753	0.96790	22.9	0.0758
76	BUS-76	100	0.9520	0.9582	21.8	1
118	BUS-118	100	0.94741	0.9503	21.9	0.5790

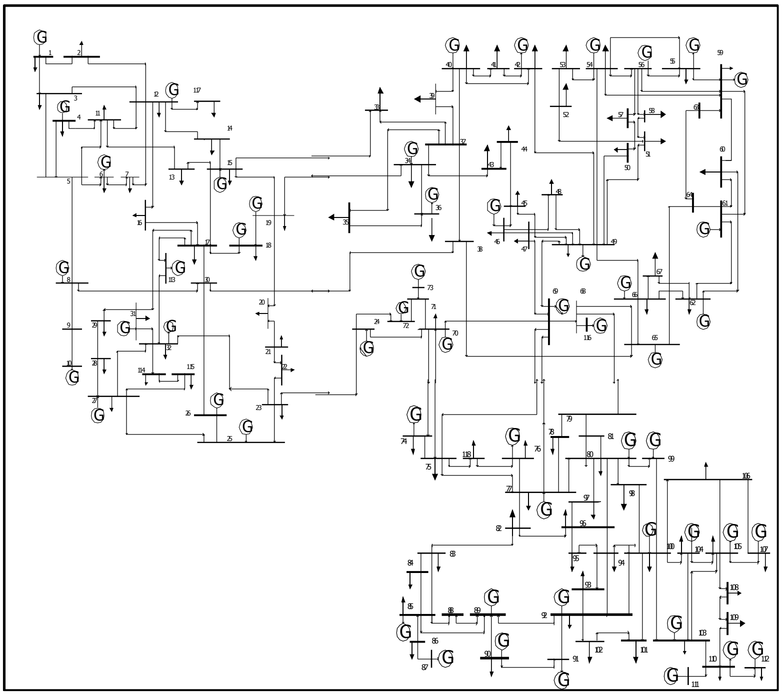


Figure 11: The IEEE 118-bus test case

Chapter 5

Conclusions and future works

5.1. Conclusions

Divergence problem of power flow is treated successfully with the proposed method by controlling switched shunts to reduce mismatch of N-R method. The optimal control of switched shunts is given when minimizing the load mismatch. Since $[-\mathrm{H}]^{\mathrm{T}}[-\mathrm{H}]$ is a full matrix, it is difficult to handle with large size. Therefore, Zones must be chosen in order to ensure ability to solve and achieve a good approximation.

5.2. Future works

Since the proposed method does not take in account the constraints of reactive power compensation, in order to improve the program and apply in the real-life, it is necessary to examines how the limits affect the method's performance. The idea of control based on the sensitivities of mismatch with respect to vector control u [10], [15] can be combined with the proposed method to find a better control strategy.

Based on this program, a new feasible boundary which pertains to the system correcting ability can be found. This information is meaningful with the system operators, in a sense they have a good feel of the current system.

Bibliography

[1] C. W. Taylor, "*Reactive Power Compensation and Voltage Stability: Removing Transmission Limitations*", Seminar Book, 1997.

[2] Y. Tamura, K. Sakamoto. Y. Tayama, "Voltage Instability Proximity Index (VIPI) Based on Multiple Load Flow Solutions in Ill-Conditioned Power Systems," in *Proceedings of the 27th IEEE Conference on Decision and Control*, Austin, Texas, December 1988.

[3] F. D. Galiana, "Load Flow Feasibility and the Voltage Collapse Problem," *Proceedings of 23rd Conference on Decision and Control*, Las Vegas, Nevada, December 1984.

[4] M. G. O'Grady. M. A. Pai, "Analysis of Voltage Collapse in Power Systems," *Proceedings of 21st Annual North American Power Symposium*, Rolla, Missouri, October 1989.

[5] A. Tiranuchit and R. J. Thomas, "A Posturing Strategy against Voltage Instabilities in Electric Power Systems,'' *IEEE Trans. on Power Systems*, Vol. 3, No. 1, February 1988, pp. 87-93.

[6] Performance Indexes for Predicting Voltage Collapse, EPRI EL-6461, Project 1999-10, Electric Power Research Institute, July 1989.

[7] Oak RiDERe National Laboratory, Engineering Science & Technology Division, Reactive Power and Importance to Bulk Power System. [Online] Available: http://www.ornl.gov/sci/decc/RP%20Definitions/ Reactive%20Power%20Overview_jpeg.pdf

[9] Overbye, T. J., "A power flow measure for unsolvable cases", IEEE Trans. Power Syst., Vol. 9, No. 3, pp. 1359-1365, August 1994.

[10] Overbye, T. J., "Computation of a practical method to restore power flow solvability", IEEE Trans. Power Syst., Vol. 10, No. 1, pp. 280-287, February 1995.

[11] Dobson, I., "Observation on the geometry of saddle node bifurcation and voltage collapse in electrical power systems", IEEE Trans. Circuits and Systems, Vol. 39, No. 3, pp. 240-243, March 1992.

[12] Dobson, I., and Lu, L., "New methods for computing a closet saddle node bifurcation and worst case load power margin for voltage collapse", IEEE Trans. Power Syst., Vol. 8, No. 3, pp. 905-913, August 1993.

[13] Van Cutsem, T., "An approach to corrective control of voltage instability using simulation and sensitivity", IEEE Trans. Power Syst., Vol. 10, No. 2, pp. 616-622, May 1995.

[14] Granville, S., Mello, J. C. O., and Melo, A. C. G, "Application of interior point methods to power flow unsolvability", IEEE Trans. Power Syst., Vol. 11, No. 2, pp. 1096-1103, May 1996.

[15] Feng, Z., Ajjarapu, V., and Maratukulam, D. J., "A practical minimum load shedding strategy to mitigate voltage collapse", IEEE Trans. Power Syst., Vol. 13, No. 4, pp. 1285-1290, November 1998.

[16] A. N. Wilson, "On the solutions of equations for nonlinear resistive networks" The Bell System Technical Journal, 1758.

[17] J Thorp and D Schulz, M Ilic-Spong, "Reactive power-voltage problem: conditions for the existence of solution and localized disturbance propagation".

[18] F.F. Wu, Y.K. Tsai, and Y.X. Yu, "Probabilistic steady-state and dynamic security assessment," IEEE Trans. on Power Systems, vol. PWRS-3, pp. 1-9, Feb. 1988.

[19] F. Merce et al., "A framework to predict voltage collapse in power systems, IEEE Trans. on Power Systems, vol. PWRS-3, pp.

[20] F.L. Alvarado et al., "Engineering foundations for the determination of security costs," IEEE Trans. on Power Systems, vol. 1807-1813, NOV. 1988. PWRS-6, pp. 1175-1182, Aug. 1991.

[21] B. Stott and J.L. Marinho, “Linear programming for power- system network security applications," IEEE Trans. on Power App. and Sys., vol. PAS-98, pp. 837-848, May/June 1979.

[22] T.J. Bertram, K.D. Demaree, and L.C. Dangelmaier, "Anintegrated package for real-time security enhancement," IEEE Trans. On Power Systems, vol. PWRSJ, pp. 592-600, May 1990.

[23] Assef Zobian and Marija D. Ilíc, “A steady state voltage monitoring and control algorithm using localized least square minimization of load voltage deviations”. *IEEE Trans. Power Delivery*, vol. 11, Issue 2, pp. 929 - 938, May 1996.

[24] Christopher Tufon, Alan Isemonger, Brendan Kirby, Fran Li, John Kueck. “A Tariff for Local Reactive Power Supply”, IEEE PES T&D Conference, April 24, 2008. [Online] Available: info.ornl.gov/sites/ publications/Files/Pub10695.ppt

[25] P Lagonotte “Structural analysis of the electrical system: application to secondary voltage control in France”, IEEE Transactions on Power Systems, Vol. 4, No. 2, May 1989

[26] Vu, H., Pruvot, P., Launay, C. and Harmand, Y. “An improved voltage control on large-scale power system”, IEEE Transactions on Power Systems, vol. 11, no. 3, pp. 1295–1303, 1996.

[27] Corsi, “The secondary voltage regulation in Italy, In Power Engineering Society Winter Meeting, vol. 1, pp. 296–304 IEEE.

[28] K Tomsovic, “Designing the Next Generation of Real-Time Control, Communication, and Computations for Large Power Systems”, Special Issue on Energy Infrastructure Systems, 2003.

[29] Chien-Ning Yu, Yong T. Yoon, Marija D. Ilíc and A. Catelli, “On-line voltage regulation: the case of New England”. *IEEE Trans. Power Delivery*, vol. 14, issue 4, pp. 1477 - 1484, Nov 1999.

[30] Sangsoo Seo, Sang-Gyun Kang, Byongjun Lee, Tae-Kyun Kim and Hwachang Song; “Determination of reactive power compensation considering large disturbances for power flow solvability in the Korean power system”, Journal of Electrical Engineering & Technology Vol. 6, No. 2, pp. 147~153, 2011.

[31] S. Iwamoto and Y. Tamya, "A load flow calculation method for ill-conditioned power systems”, IEEE Trans. Power App. and Sys., vol. PAS-100, pp. 1736-1743, April 1981.

[32] Prabha Kundur, “*Power system stability and control*”, McGraw-Hill, Inc., 1993.

[33] Luciano V. Barboza, Roberto Salgado, “Corrective solutions of steady state power system via Newton Optimization method”, SBA Controle & Automação Vol. 11 no. 03 / Set., Out., Nov, December de 2000.

[34] Andre G.C. Conceicao and Carlos A. Castro, “A new approach to defining corrective control actions in case of infeasible operating situations”, IEEE Porto Tech Conference, Portugal, 2001.

[35] "Transmission system reliability methods - mathematical models, computing methods and results, EPRI Report EL-2126, July 1982.

[36] Arthur R. Bergen and Vijay Vital, “*Power system analysis*”, 2nd ed., PRENTICE HALL, 2000.

[37] J. Duncan Glover, Mulukutla S. Sarma, Thomas J. Overbye, “*Power system analysis and design*”, 4th ed., Thomson Learning, 2008.