Title page:

Title: A quick solution to optimal coordinated voltage-control, based on dimension-reduction of power system via Modified Ward-PV

Author names and affiliations:

Mandana Hojati Tabatabaei: Postal address: Department of Electricity Engineering, South Tehran Branch, Islamic Azad University, Mahallati Exp. Tehran, Iran. postal code: 1388834669 ; m.h.tabatabaiee2007@gmail.com; telephone and cell phone: 02144531783;09126952416.

Hassan Siahkali: Postal address: Department of Electricity Engineering, South Tehran Branch, Islamic Azad University, Mahallati Exp. Tehran, Iran. Postal code: 1777613651; h_siahkali@azad.ac.ir; telephone and cell phone: 02133722831; 09123088158.

Javad Olamaei: Postal address: Department of Electricity Engineering, South Tehran Branch, Islamic Azad University, Mahallati Exp. Tehran, Iran; postal code: 1777613651; J.olamaei@azad.ac.i; telephone and cell phone: 02133722831; 09123301679.

Corresponding author:

Hassan Siahkali: Postal address: Department of Electricity Engineering, South Tehran Branch, Islamic Azad University, Mahallati Exp. Tehran, Iran. Postal code: 1777613651; h_siahkali@azad.ac.ir; telephone and cell phone: 02133722831; 09123088158.
A quick solution to optimal coordinated voltage-control, based on dimension-reduction of power system via Modified Ward-PV

Mandana Hojati Tabatabaei, Hassan Siahkali*, Javad Olamaei

Department of Electricity Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran

*Corresponding author email: h_siahkali@azad.ac.ir

Abstract: Voltage control and Voltage stability are the most important issues in the power system. The purpose of this paper is to investigate the emergency voltage control in power systems. One of the most important proposed methods to solve this issue is optimal coordinated voltage control (OCVC), which is based on the model predictive control (MPC). Time limitations for preventing voltage collapse is the most critical constraint to solve an OCVC problem. In this paper, the Modified Ward-PV will be proposed to reduce the dimension of the power system and consequently, the speed of solving problem is increased. In this method, immediately after occurrence a fault, the power system is partitioned to into three subsystems by spectral graph partitioning method. Partitioning is based on reactive power flow through the lines. The subsystems, which are far from fault, will be replaced by the reduced model. This method will drastically reduce the number of system equations and will boost the speed of solving problem. The simulations results obtained on New England IEEE 39-Bus System reveals that the proposed method acts more precise than dimension reduction of power system based on linearization of external subsystems, but the speed of solving problem decrease.

Key words: Voltage stability, Modified Ward-PV, OCVC, Reducing the system dimensions.

1. Introduction:

Voltage stability is one of the main concerns of the power systems. Based on IEEE/CIGRE definition, voltage stability is the ability of the power system to maintain an acceptable steady state voltage for all buses, after a disturbance [1, 2].
Voltage collapse is a severe voltage drop of the power system due to voltage instability. If there is a voltage drop at some buses, it may be compensated by generators or other reactive power compensators, and the voltage status will remain to normal mode. Otherwise if system involves another problem, the voltage drop may be more severe and the under-voltage relays cause outage of some generators and consequently the voltage drop in the system becomes more severe and finally a blackout occurs. A worldwide study of blackouts in the world confirms that the cause of most of these blackouts is a voltage drop [3, 4]. In addition to a lot of economic damage, these blackouts will also cause people to be dissatisfied with the electricity network. Therefore, rapid identification of unstable conditions and performing appropriate control actions will play a significant role in increasing the quality and security of the system.

Voltage control is performed in two ways in a power system, which are preventive and emergency control. The set of actions which are applied before a fault occurrence to improve profile voltage are called preventive, while emergency control is a set of control actions which are applied after occurring a fault in the power system to prevent the voltage collapse. The present study aims to investigate the emergency voltage control. The most important factor in investigating the problem of emergency voltage control is the time shortage. Because if the required control actions are not applied on the power system at the right time, the power system will be out of its absorption area and subsequently voltage collapse will definitely occur [5-8].

To prevent voltage collapse in a power system, we can use an optimal coordinated and proper arrangement of control actions which is called optimal coordinated voltage control (OCVC)[9]. Nowadays, coordinated voltage control (CVC) is successfully implemented in France, Italy, Belgium, and Switzerland [10-14]. However it should be noted that CVC requires more research in large power systems and many researchers are investigating in this field now.

Figure (1), represents the structure of all previous papers dealing with emergency voltage control. Some papers have addressed the issue in multi-area power systems in which each area is exclusively devoted to its own operator and has no access to any information from other areas. The Lagrangian decomposition is proposed to solve the emergency voltage control problem in multi-area power systems [15-22]. In the
papers dealing with emergency voltage control in single-area, it is assumed that the power system operator is aware of all system parameters at any time and can use all available control actions to control the system [23-47]. The purpose of this paper is to investigate the problem of emergency voltage control in a single-area system and it is assumed that all system parameters, such as voltage, current, fault location, and so on are available.

The papers dealing with single-area power systems can be categorized into two groups: 1- Decentralized Voltage Control [42-45], and 2- CVC based on Model Predictive Control (MPC) method [23-41, 46]. These two categories are divided into 4 groups (A) to (D) in Figure (1).

The power system equations in the emergency voltage control problem are differential-algebraic, and the nature of its control variables is a combination of discrete and continuous variables. Thus, the OCVC is an optimization problem with a high complexity degree. Therefore, the need for a proper and fast control system in the OCVC issue is felt more. Features of a good and complete method to solve emergency voltage control problem are as follows:

1) It shall consider all equality and inequality constraints.

2) It shall be an adaptive method to be able to adapt by changing the operating point.

3) As far as possible, do not use the load shedding to control the system.

4) It should be an optimal method. As far as possible, the optimal control actions just be applied.

5) It shall have appropriate flexibility. It means the operator has the opportunity to choose the optimal solution from the set of non-dominated solutions which are obtained by solving a multi-objective optimization problem.

6) It shall have a good performance against unanticipated fault. Any disturbance except the outage of a line or the outage of a generator is called an unanticipated fault.

7) It shall have a good performance against consecutive faults.

8) It shall be able to determine the optimal solution with the appropriate speed.

9) It can be used in large power systems.
Based on these 9 features, papers of group (A) to (D) are compared in Table (1).

In the decentralized control strategy, each distributed energy source works freely utilizing measured local signals [7, 48]. In the papers of group (A) by the title of decentralized voltage control, the power system is initially partitioned into several subsystems, and for each subsystem one control system and one performance index are defined. Whenever the performance index of one subsystem is greater than 1, the control actions of that subsystem will be implemented continuously with an interval of 5 seconds. Fast recovery of the voltage is the advantage of this method, but its disadvantages include the lack of optimal control actions, and the great number of control actions which make the control system more costly [42-45].

In the Papers of group (B) to (C), the emergency voltage control method is based on MPC. MPC is similar to Proportional Integral Derivative (PID) control methods, except that in PID-based controllers, control measures are determined according to the feedback received from the output and applied on the system, but in the MPC method, the behavior of the power system is predicted in the future by applying a set of control actions on the system at the moment [33]. MPC has been used to control various issues in the power system[49, 50]. In MPC-based coordinated voltage control, optimal control measures are determined by solving the single or multi-objective optimization problem. The objective functions generally include tracing the reference voltage, reducing the number of control actions, and minimizing the load shedding. In the group (B), tree search, Evolutionary algorithm, heuristic search, pseudo-gradient, Particle Swarm Optimization (PSO) algorithm are generally used to solve the single objective problems [23-35]. The main advantage of group (B) papers is finding the optimal control actions, but due to solving the single-objective optimization, the proposed method does not have the flexibility feature. In order to overcome this disadvantage, group (C) of papers have been suggested which solve a multi-objective optimization [36-40, 46]. By solving the multi-objective optimization, a set of non-dominated solutions are obtained, the system operator has the opportunity to choose the best control actions from the operational, economic or environmental points of view and apply it on the system according to the system conditions. In this case, it is stated that the control system has the flexibility feature.
But solving methods of optimization problems are generally iterative and consequently, they are so time consuming. To improve the speed of the control system, the calculations are done in online and offline parts [36-40]. Offline calculations provide an appropriate knowledge base which can be used for online part. Nevertheless, the speed of the control system is not suitable for solving the emergency voltage control in large power systems. So the papers of group (D) have been proposed. In [41], the similar method to [36-40] is utilized to solve the OCVC problem, with one big difference for increasing the speed, arguing that the voltage instability in the early moments is a local phenomenon, so the areas which are far from the fault location, have been replaced by the dimension reduction method based on linearization, and as a result, the number of equations of the system is reduced and finally the speed of control method is increased. By linearization of the external subsystems, their equations and their external control variables are linearized, which reduce the accuracy of solving the optimization problem.

Due to nonlinearity and complexity of the power system, operators and scientists of the electricity industry always try to find a way to reduce power system dimensions and subsequently calculation time. Ward and Ward-PV methods can be mentioned as methods to reduce the dimensions of the power system [51]. The advantage of Ward-PV method over Ward method is the preservation of PV buses at the external subsystems to control of the system. It can be predicted that, due to the greater number of equations, calculations may take more time consuming comparing to the linearization method.

In this paper, due to the use of susceptance of capacitors for OCVC, the Ward-PV method has been modified, and beside to PV buses, capacitors buses are also preserved in the external areas. The main innovations of this paper are as follows:

1- Due to solving the multi-objective optimization problem that will be described completely later, the proposed method has the features 1 to 7, which mentioned above, and because the proposed method is based on reducing the system dimensions by Modified Ward-PV, features 8 and 9 are also included. Therefore, the proposed method is a comprehensive method to solve the emergency voltage control problem which will be proven by three simulation scenarios.
2- Using spectral graph partitioning method to partition the power system after occurrence a fault. An appropriate system partitioning should meet two following conditions: (a) the effect of fault on voltage of external buses should be lower than internal ones, (b) after fault occurrence, buses with larger effect on restoration of fault zone voltages should be placed in fault zone. In [39-45, 51-53] the system is partitioned before the fault so partitioning does not take into account these two conditions.

3- Due to the correlation between the reactive power and voltage, partitioning is based on reactive power flow. In [41], partitioning is based on the admittance matrix of the system, but if the occurring fault is outage of a generator, or changing the load of the system, the admittance matrix of the system will not change. Thus, partitioning based on admittance matrix cannot be precise.

4- Reducing the power system dimension by a Modified Ward-PV method. One of the advantages of this method is retaining effective control variables in recovering voltage of subsystem which are far from the fault location. It is more precise than the linearization which was introduced in [41].

The structure of the paper is as follows: in section two, the power system model is expressed in the emergency voltage control problem. Section three is devoted to the OCVC, objective functions, and multi-criteria decision making (MCDM). Section four deals with the Modified Ward-PV technique for reducing the dimensions of the power System. The proposed algorithm of the problem is completely introduced in section five. Section six is devoted to simulations using three scenarios, and finally the results of the paper are presented in section seven.

2. Model of Power System in Emergency Voltage Control:

The power system model in the emergency voltage control includes a set of differential-algebraic equations, expressed as Equation (1) and Equation (2).

\[ \dot{x} = f(t, x, y, u) \quad \text{Equation (1)} \]

\[ 0 = g(x, y, u) \quad \text{Equation (2)} \]
Here, $x, y, u$ are the state variables, the algebraic variables, and control actions, respectively. Since we intend to study long-term voltage instability problems, the quasi-steady-state approximation of generators would be sufficient to capture the essential behavior of the system. Hence the differential equations of the system are the only the differential equations of the loads. The aggregate exponential recovery load model has been used in this paper, in which the equations are as follow \cite{33, 41, 42}:

$$\frac{dx_{i,p}}{dt} = -\frac{x_{i,p}}{T_{i,p}} + P_{i,0}\left(V_i^{\alpha_s} - V_i^{\alpha_t}\right)$$  \hspace{1cm} \text{Equation (3)}

$$P_{i,d} = \left(1-n_{i,d}D_{\text{shed}}\right)\left(x_{i,p}/T_{i,p} + P_{i,0}V_i^{\alpha_t}\right)$$  \hspace{1cm} \text{Equation (4)}

$$\frac{dx_{i,q}}{dt} = -\frac{x_{i,q}}{T_{i,q}} + Q_{i,0}\left(V_i^{\beta_s} - V_i^{\beta_t}\right)$$  \hspace{1cm} \text{Equation (5)}

$$Q_{i,d} = \left(1-n_{i,d}D_{\text{shed}}\right)\left(x_{i,q}/T_{i,q} + Q_{i,0}V_i^{\beta_t}\right)$$  \hspace{1cm} \text{Equation (6)}

Where $V_i$ is the voltage of bus $i^{th}$. $x_{i,p}$ and $x_{i,q}$ are the state variables that when they change, recovery of the active and reactive power in the $i^{th}$ bus is resulted. For this reason, when the voltage decrease, the values of $x_{i,p}$ and $x_{i,q}$ begin to increase to recover the power. $P_{i,d}$ and $Q_{i,d}$ are the active and reactive power of the load at bus $i$, respectively. $D_{\text{shed}}$ represents the load shedding step, and it is considered equal to 0.05pu. $n_{i,d}$ is the number of load shedding steps at the bus $i$. $T_{i,p}$ and $T_{i,q}$ are time constants of the active and reactive power loads, respectively. $T_{i,p}$ and $T_{i,q}$ change from several ten seconds to several minutes based on recovery factor. In this paper, these values are assumed to be 60 seconds. $\alpha_s, \alpha_t, \beta_s$ and $\beta_t$ are constant factors that show the amount of dependence of active and reactive power of loads on steady and transient states. $\alpha_t$ and $\beta_t$ are always greater than $\alpha_s$ and $\beta_s$, which means the load dependence on the voltage in the transient state is greater than the steady state. In this paper, the control parameters include
susceptance of the capacitors, the reference voltage of each generator, on-load tap changers (OLTC), and load shedding.

3. OCVC:

The concept of CVC refers to coordinated utilization of resources to control reactive power of the system simultaneously. It is proved that coordinated utilization of control equipment in different locations, instead of utilization of big control equipment in one place, is more efficient in improving system condition. For the first, the MPC was proposed to solve the CVC problem in [33]. In this paper, MPC is used to solve the OCVC problem. Figure (2), shows the structure of OCVC based on MPC. According to Figure (2), control variables \( u \) are selected with a point of view to the future and applied on the power system. For this work the variables \( x \) and \( y \) of the system are first sampled. After that, based on sampled values, for each arrangement of control actions \( (u) \), the output of the system \( \hat{y} \) is predicted. Subsequently the control actions of outputs which are closer to the reference value \( (y_r) \), will be applied on the system. In OCVC, \( \hat{y} \) is the voltage of buses. The Euler method will be used to predict the response path \( \hat{y} \) [33].The OCVC problem is considered as a multi-objective optimization problem such as [36-41]. By solving the multi-objective optimization, a set of non-dominated solutions is obtained. Therefore, the system operator has the opportunity to choose the best control actions from the operational, economic or environmental points of view and apply it on the system according to the system conditions. This work is done by helping MCDM technique. These three objective functions are as follow:

\[
J_{V_i} = \min \sum_{i=0}^{t_p} \left[ v_i - v_{iref} \right] dt
\]

Equation (7)

\[
J_{act} = \min n_c
\]

Equation (8)

\[
J_{load} = \min \sum_{i,d} n_{i,d}
\]

Equation (9)
Where $J_{\sum Vi} J_{act}$ and $J_{load}$ are tracing reference voltage, number of control actions and load shedding, respectively. $v_{it}$ is voltage of bus $i$ at time $t$, $v_{iref}$ is reference voltage of bus $i$ which is assumed to be 1pu. $t_p$ and $t_0$ are the prediction interval and the moment of applying control actions, respectively. The number of control actions applied on the system is shown by $n_c$, and $n_{i,d}$ is the number of load shedding steps in bus $i$. Like [36-41] jumping genes paradigm optimization algorithm is proposed to solve multi objective optimization problem.

3.1. MCDM:

After determining a set of non-dominated solutions, the system operator can use the MCDM technique to determine the best answer and apply it on the system. This technique is completely explained in [37-40]. With 3 objective functions, and $n$ optimal non-dominated solutions, the solutions will be ranked based on Equation (10), and finally the first rank solution will be applied on the system:

$$r_i = \sum_{j=1}^{3} w_j a_{ijn}$$

Equation (10)

Where $r_1,...,r_n$ are the final rank of non-dominated solutions $A_1,...,A_n$ respectively Table (2). $w_1, w_2$ and $w_3$ show respectively the relative importance of $J_{\sum Vi}, J_{act}$ and $J_{load}$ obtained from Equation (12). $a_{ijn}$ is the normalized value $a_{ij}$, is calculated from Equation (11):

$$a_{ijn} = \frac{\Gamma(a_{ij} - a_{wj})}{(a_{bj} - a_{wj})} + 1$$

Equation (11)
By assuming $\Gamma = 99$, $a_{ij}$ values fall in the span $[1,100]$. Also $a_{bj}$ and $a_{wj}$ are respectively the best and worst values for the objective function $J_j$. To determine $w_j$, firstly we must form a preference matrix Table (3) in which $m_{ii} = 1$ and $m_{ij} = \frac{1}{m_{ji}}$. The expression $m_{ij}$ represent that $J_i$ possesses a value $m_{ij}$ times $J_j$. For example, if $m_{23}$ is assumed to be 3, the importance of the objective function $J_2$ is three times of objective function $J_3$. Then:

$$Mw = \lambda_{\text{max}}w$$

Equation (12)

In which $\lambda_{\text{max}}$ is the maximum eigenvalue of the preference matrix $M$ and $w$ the eigenvector of this eigenvalue.

4. Reducing the System Dimensions:

Modern power systems are interconnected to provide acceptable levels of reliability. Each energy management system (EMS) is only appropriate for a small part of this interconnected system that is called the internal zone. The rest of the system, which is not monitored by EMS, is called the external zone. For effective monitoring of the internal zone and evaluating its security, it is necessary to consider a suitable model for the external zone. The model of the external zone should properly represent the impact of the external zone on the internal one. For studies such as emergency voltage control, if the external zone is modeled in great detail, the complexity of the problem will be high. Hence, the reduced models are utilized for external zones. Different methods are used for reducing the dimension of the system. For example, Ward and Ward-PV are two static methods in reducing the dimensions of the power system where are shown in Figure (3)-(A) and (B). On the other hand, we know that the voltage instability phenomenon is only a local issue in early stages of occurrence in the power system [45], in result, Ward and Ward-PV can be used for zones which are far from fault. The Ward-PV method used in this paper has been modified comparing to
the method presented in [41]. In Ward method all external buses have been removed from the system and in Ward-PV method, only PV buses of external zones remain and other buses removed from the model, while in proposed Modified Ward-PV, capacitor buses, as well as PV ones, remain in the system. Figure (3)-(C) shows the Modified Ward-PV model.

To reduce the power system dimensions, it should be partitioned immediately after the fault. A power system can be assumed as a graph in which buses comprises the set of vertexes, and the line between two buses is the branch of the graph [54]. The amount of each branch equals reactive power flow from the line immediately after the fault. Consequently, the power system is partitioned in a way that the sum of reactive power flow between branches of sub-areas will be minimized. In other words, areas can be independent in supplying the needed reactive power and preserving their voltages as far as possible.

After partitioning the power system and determining the external areas, which are far from the fault, the Modified Ward-PV will be implemented on the system. The Modified Ward-PV method is similar to Ward-PV, except that the capacitive buses are preserved in the external area. The following equations is displayed Ward-PV procedure. To preserve the external system PV buses, $Y_{QQ}$ and $Y_{VV}$ are the admittance matrix of PQ and PV buses in external zone, respectively.

$$
\begin{bmatrix}
Y_{QQ} & Y_{QV} & Y_{Qb} & 0 \\
Y_{VQ} & Y_{VV} & Y_{Vb} & 0 \\
Y_{bQ} & Y_{bV} & Y_{bb} & Y_{bi} \\
0 & 0 & Y_{ib} & Y_{ii}
\end{bmatrix}
\begin{bmatrix}
E_Q \\
E_V \\
E_i
\end{bmatrix}
= 
\begin{bmatrix}
I_Q \\
I_V \\
I_i
\end{bmatrix}
$$

Equation (13)

To remove external system PQ buses, voltage vector $E_Q$ must be removed from Equation (13). So, $E_Q$ is obtained from the first row of Equation (13):
\[ Y_{QQ}E_Q^* + Y_{QV}E_V^* + Y_{Qb}E_b = I_Q \]  
\[ E_Q = Y_{QQ}^{-1}\left(I_Q - (Y_{Qb}E_b + Y_{QV}E_V)\right) \]  

By replacing \( E_Q \) in the second and third rows of Equation (15), there would be:

\[
\left(Y_{Vb} - Y_{VQ}Y_{QQ}^{-1}Y_{Qb}\right)E_b + \left(Y_{VV} - Y_{VQ}Y_{QQ}^{-1}Y_{QV}\right)E_V = I_V - \left(Y_{VQ}Y_{QQ}^{-1}I_Q\right)
\]

\[
\left(Y_{bV} - Y_{bQ}Y_{QQ}^{-1}Y_{QV}\right)E_V + \left(Y_{bb} - Y_{bQ}Y_{QQ}^{-1}Y_{Qb}\right)E_b + Y_{bb}^iE_v + Y_{bi}E_i
\]

\[ = I_b - Y_{bQ}Y_{QQ}^{-1}I_Q \]

Equation (17)

According to Equation (16) and Equation Error! Reference source not found.:

\[ I_{eqV} = Y_{VQ}Y_{QQ}^{-1}I_Q \]  
\[ I_{eqb} = Y_{bQ}Y_{QQ}^{-1}I_Q \]

Equation (17)  
Equation (18)

Where \( I_{eqV} \) is the extra injection current in external PV buses, and \( I_{eqb} \) is the extra injection current in boundary buses. Considering Equation Equation (13), \( Y_{eq} \) is as follows:

\[ Y_{eq} = \begin{bmatrix} Y_{VV} & Y_{Vb} \\ Y_{bV} & Y_{bb} \end{bmatrix} - \begin{bmatrix} Y_{VQ} \\ Y_{bQ} \end{bmatrix} \times [Y_{QQ}]^{-1} \times \begin{bmatrix} Y_{QV} & Y_{Qb} \end{bmatrix} \]  

Equation (20)

The injection complex power in boundary buses and external PV buses could be obtained from injection currents.

\[ S_{eqb} = E_b \left(Y_{bQ}^* \right) \left(Y_{QQ}^* \right)^{-1} E_Q^{-1} S_Q \]  

Equation (21)

\[ S_{eqv} = E_v \left(Y_{vQ}^* \right) \left(Y_{QQ}^* \right)^{-1} E_Q^{-1} S_Q \]  

Equation (22)

Where \( S_{eqb} \) and \( S_{eqv} \) are injection complex power in boundary and PV buses, respectively.
5. Procedure of Proposed OCVC:

After system partitioning and dimension reduction of power system, the method proposed in [39-41] is employed to solve the OCVC problem. In these papers, in order to boost speed and adaptive feature, OCVC is solved in two online and offline steps. In [39], firstly the system faults are divided into anticipated and unanticipated. The anticipated faults include outage of a line or generator from the system. Any other fault in the system, or combination of several anticipated faults, can be considered as an unanticipated fault. Then, for each anticipated fault, the OCVC is solved in offline mode and a set of non-dominated solutions is obtained and saved in the knowledge base of control system. Since there is no time limitation, the number of initial population and the number of iterations of offline calculations are both assumed to be 100 and also the offline calculations will be done in an unreduced system.

Whenever the an anticipated fault occurs in the power system, the existing data relevant to this fault in knowledge base is recalled to be applied on the system, but because of possibility of a change in operating point of the system when the fault occurs in [40, 46], a local search system is introduced to update the set of solutions existing on the knowledge base. Therefore, the initial population of 10 cases is selected from the knowledge base. The initial population is chosen in way to have a good diversity. To this end, the crowding distance concept is employed. The number of iterations of local search is considered to be 10. This method is adaptable with any operating point in the power system. Hence, it is called an adaptive method.

If an unanticipated fault occurs on the system, in the first step the location of the fault is determined and the data belonging to this fault location is called from the knowledge base. Consequently, a small search space is formed [40, 41]. Then, the online learning algorithm, introduced in [40, 41], determines the appropriate solutions in this search space. In online learning, the number of iterations and initial population both are assumed to be 20. The flowchart of the proposed algorithm is presented in Figure (4).
6. Simulation results:

To investigate the performance of proposed OCVC based on Modified Ward-PV, a New England 39 bus system was employed. There are 10 generators in this system. The reference voltage of each generator is considered as a control parameter which can change from 0.9 to 1.1 pu. There are also 10 capacitors in buses 3, 4, 7, 8, 12, 15, 16, 18, 21 and 26 which change from 0 to 0.3 pu in step 0.1. There are 21 load buses on the system; consequently there are 21 locations for load shedding. The load shedding step is assumed as 0.05 pu. Moreover, due to OEL of each generator, the maximum excitation voltage of each generator is considered 2 pu. It should be mentioned that the value of reference voltage of all generators and capacitors in their basic states are assumed 1 and 0 pu, respectively. It is assumed that all the required parameters such as voltage, current, active and reactive power, and the location of the fault are available. A core i7 computer with a 1.6 GHz processor is used for simulations. Three scenarios will be reviewed in this section:

**Scenario I:** An anticipatable fault occurs, outing generator 32, with two goals:

1- Comparison of methods based on dimension reduction: Modified Ward-PV and linearization method introduced in [40]. The following index is used to achieve this goal.

\[
CI = \frac{100}{(N_L \times \Delta t)} \sum_{i} \sum_{t} \left| \frac{V_{i,t} - \bar{V}_{i,t}}{\bar{V}_{i,t}} \right|
\]

Equation (19)

Where \( V_{i,t} \) and \( \bar{V}_{i,t} \) are respectively voltages of bus i at time t, in two reduced and unreduced systems. \( N_L \) and \( \Delta t \) are respectively the number of buses and the time which the control system takes to be executed.

2- Investigation of the role system partitioning before and after fault.

**Scenario II:** The simultaneous outage of line 21-22 and an %20 overload in bus 21 which is an unanticipated fault to test the performance of the proposed method in case of unanticipated fault. **Scenario III:** The purpose of this scenario is to evaluate the performance of the proposed method against consecutive
faults. So, generator 32 and line 6-7 tripped at two different times. This fault is considered an unanticipated fault.

The algorithm proposed to solve a multi objective optimization problem is jumping genes paradigm optimization algorithm [34-40]. In Table (4), the preference matrixes are represented from tracing reference voltage and economic consideration (minimization the number of control actions) to choose the best non-dominated solution and its application on the system. In all scenarios, it is assumed that the fault occurs at second 30. The control actions will be in times 60s, 90s, 120s and etc.

6.1. Scenario I:

With outage of generator 32, as can be seen in Figure (5), the voltage of the power system has been collapsed without any control system. Outage of generator 32 is an anticipated fault which formerly the OCVC problem was solved in an offline mode with an initial population 100 and iteration number 100. Consequently, there is a set of non-dominated solutions in knowledge base for this fault. The priority is exploitation of optimal solutions without any load shedding. There are 14 sets of non-dominated solutions without load shedding in the knowledge base for outage of generator 32. That control system as shown in Figure (6), 10 superior solutions are chosen based on crowding distance concept from 14 possible solutions to form the initial population for local search. They are marked with “o”.

In this scenario, to check the adaptability of the control method, all loads have randomly changed from 0.95 to 1.05 of the basic load.

Figure (7) depicts power system partitioning into three subsystems, based partitioning before and after fault. The zone 1 in which the fault has occurred is considered as the internal subsystem and two other subsystems are the external subsystems. As can be seen, with outage of generator 32 if the power system is partitioned after occurring the fault, the generator 30 will be in the internal zone due to its role in voltage recovery. If it is partitioned before occurring the fault the generator 30 will be in the external zone. Therefore, it is better to do the partitioning after the fault occurrence.
For precise evaluation of both methods (Modified Ward-PV and Linearization), it is assumed that the OCVC problem is solved by two methods and the control variables are applied on unreduced system (complete model of the system). A good comparison between answers of Modified Ward-PV and Linearization method with unreduced model is given in the Table (5). It is resulted that the Modified Ward-PV is twice more precise than linearization, but the speed of method is lower than linearization method. The time needed for search in the unreduced system is about 16 seconds, but as is seen in Table (5), the same time will be reduced to 8.5 and 11.4 seconds in linearization and modified Ward-PV methods respectively. This is because of number of equations, as can be seen in Table (6).

Figure (8) and Figure (9) show the voltage of bus 11 in presence of introduced control systems with two objective functions of tracing reference voltage and minimizing control actions. Thus, the following results are obtained from this scenario:

1- Adaptability of both methods (Linearization and Modified Ward-PV) due to alteration of operating point.

2- Higher speed of linearization method compared to Modified Ward-PV, which, of course, has led to less accuracy.

3- In order to respect customer’s right, the numbers of load shedding in both methods for objective functions of tracing reference voltage and minimizing control actions are equal to zero

4- Flexibility of both methods due to solve multi-objective optimization.

6.2. Scenario II:

In this scenario, line 21-22 is outed, simultaneously, there is an overload of 20% in bus 21. Due to this fault, there will be a voltage collapse in absence of any control system, as is depicted in Figure (10). Figure (11) represent the system partitioning after fault. This fault is an unanticipated fault. So by occurring this fault, all data of buses 21 and 22 which has been saved in knowledge base, called to form the initial population of online learning. Table (7) and Table (8) are devoted to a comparing the results of two Modified Ward-PV and Linearization methods. As can be seen in this scenario, the accuracy of the Modified
Ward-PV method is much better than the Linearization method, while the speed of the Linearization method is higher than that of the Modified Ward-PV.

In Figures (12) and (13), the voltage of bus 21 is demonstrated from points of view the tracing reference voltage and minimizing the number of control actions.

6.3. Scenario III:

To evaluate the performance of the proposed method against consecutive faults, another scenario with two different simulations, was considered. In both cases, first and second faults are considered as outage of generator 32 and outage of line 6-7 respectively. First fault was occurred at $t = 30s$ for both simulations, while the second one occurred at times 75s and 105s. Because the second fault occurs a short time after the first fault, these two faults are considered as a combined and unanticipated fault. The performance of the control system against these consecutive faults by considering tracing reference voltage is shown in Figure (14). The number of control actions and load shedding steps is presented in Table (9).

7. Conclusion:

A quick method to solving the OCVC problem, based on reducing the dimensions of the power system by Modified Ward-PV is presented. For this purpose, after occurring fault in the power system, it is partitioned to reduce the dimensions of the system. The partitioning is based on minimizing the reactive power flow from the lines which there are between subsystems. After partitioning, the zone in which the fault has occurred is considered as the internal subsystem. Since the voltage instability phenomenon is only a local issue in early stages of occurrence in the power system, so the external area can be replaced by equivalent model. Therefore we can use the Modified Ward-PV to reduce the size of power system while maintaining the performance accuracy. The simulations results obtained on New England IEEE 39-Bus System reveal that the proposed method is adaptive, flexible and usable in large power system. Also, it acts more preciseness than linearization method, but on the other hand, the speed of solving problem decreased.

8. References:
[1] Kundur, P., Paserba, J., Ajjarapu, V. et al. “Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions”, *Int. J. IEEE Transactions on Power Systems.*, 19(3), pp. 1387-1401 (2004).

[2] Rabiee, A., Mohseni-Bonab, S.M., Parniani, M. et al. “Optimal cost of voltage security control using voltage dependent load models in presence of demand response”, *Int. J. IEEE Transactions on Smart Grid.* 10(3), pp. 2383-2395 (2018).

[3] Taylor, C. W. and Erickson, D. C. “Recording and analyzing the July 2 cascading outage [Western USA power system]”, *Int. J. IEEE Computer Applications in Power.* 10(1), pp. 26-30 (1997).

[4] Ye, X., Le, J., Liu, Y. et al. “A coordinated consistency voltage stability control method of active distribution grid”, *Int. J. of Modern Power Systems and Clean Energy.* 6(1), pp. 85-94 (2018).

[5] Esaka, T., Kataoka, Y., Ohtaka, T. et al. “Voltage stability preventive and emergency preventive control using VIPt sensitivities,” *Int. Conf. IEEE PES Power Systems Conference and Exposition.*, New York, USA, pp. 509–516 (2004).

[6] Voropai, N.I., Kurbatsky, V.G., Tomin, N.V. et al. “Preventive and emergency control of intelligent power systems,” 3th *Int. Conf. IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, Berlin, Germany, (2012).

[7] Antoniadou-Plytaria, K. E., Kouveliotis-Lysikatos, I. N., Georgilakis, P. S. et al. “Distributed and decentralized voltage control of smart distribution networks: Models, methods, and future research,” *Int. J. IEEE Transactions on Smart Grid.* 8(6), pp. 2999-3008 (2017).

[8] Vournas, C. and Karystianos, M. “Load tap changers in emergency and preventive voltage stability control,” *Int. J. IEEE Transactions on Power Systems.* 19(1), pp. 492-498 (2004).

[9] Gu, M., Meegahapola, L. G. and Wong, A. K. “Coordinated Voltage and Frequency Control in Hybrid AC/MT-HVDC Power Grids for Stability Improvement,” *Int. J. IEEE Transactions on Power Systems.* 36(1), pp. 635-347 (2021).
[10] Corsi, S., Pozzi, M., Sabelli, C. et al. “The coordinated automatic voltage control of the Italian transmission Grid-Part I: Reasons of the choice and overview of the consolidated hierarchical system,” Int. J. IEEE Transactions on Power Systems. 19(4), pp.1723-1732 (2004).

[11] Corsi, S., Pozzi, M., Sforna, M. et al. “The coordinated automatic voltage control of the Italian transmission grid-Part II: control apparatuses and field performance of the consolidated hierarchical system Reasons of the choice and overview of the consolidated hierarchical system,” Int. J. IEEE Transactions on Power Systems. 19(4), pp. 1733-1741 (2004).

[12] Geidl, M. “Implementation of coordinated voltage control for the Swiss transmission system,” 15th Int. Conf. IEEE Mediterranean Electrotechnical Conference., Valletta, Malta, (2010).

[13] Van Hecke, J., Janssens, N., Deuse, J. et al. “Coordinated voltage control experience in Belgium,” In COORDINATED VOLTAGE CONTROL IN TRANSMISSION NETWORK, p.CIGRE, pp .24-25, (2007).

[14] Paul, J., Leost, J. and Tesseron, J. “Survey of the secondary voltage control in France: Present realization and investigations,” Int. J. IEEE Transaction on Power Systems. 2(2), pp. 505–511 (1987).

[15] Beccuti, A.G., Demiray, T.H., Andersson, G. et al. “A Lagrangian decomposition algorithm for optimal emergency voltage control,” Int. J. IEEE Transactions on Power Systems. 25(4), pp. 1769–1779 (2010).

[16] Wang, X., Wang, C., Xu, T. et al. “Optimal voltage regulation for distribution networks with multi-microgrids”, Int. J. ScienceDirect. Applied Energy. 210, pp. 1027-1036 (2018).

[17] Granada, M., Rider, M. J., Mantovani, J. et al. “A decentralized approach for optimal reactive power dispatch using a Lagrangian decomposition method,” Int. J. ScienceDirect. Electric Power systems Research. 89, pp. 148-156 (2012).

[18] Islam, S.R., Muttaqi, K. M. and Sutanto, D. “Multi-agent receding horizon control with neighbour-to-neighbour communication for prevention of voltage collapse in a multi-area power system,” In. J. IET Generation, Transmission & Distribution. 8(9), pp. 1604-1615 (2014).
[19] Li, P., Zhang, B., Cheng, C. et al. “A distributed model prediction based method for coordinated voltage control of power system”, 10th IET. Int. Conf. on Developments in Power System Protection (DPSP 2010). Managing the Change. (2010).

[20] Van Pham, H. and Ahmed, S.N. “Multi-Agent based Approach for Intelligent Control of Reactive Power Injection in Transmission Systems”, In Dynamic Vulnerability Assessment and Intelligent Control: For Sustainable Power System. P. Wiley-IEEE Press. Ed., 1th., pp. 269 (2018).

[21] Liu, S., Li, Y., Cao, Y. et al. “Distributed model predictive control algorithms for emergency voltage stability control of power systems,” Int. Conf. IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Xi’an, China, pp. 2597-2600(2016).

[22] Vallem, M. R., Vyakaranam, B., Holzer, J. T. et al. “Power system decomposition for practical implementation of bulk-grid voltage control methods,” 19th Int. Conf. on Intelligent System Application to Power Systems (ISAP), San Antonio, TX, USA, pp. 1-6 (2017).

[23] Wang, S., Liu, M., Hu, B. et al. “Emergency voltage control based on MPC, Radau collocation and moving finite elements technique,” Int. Conf. on Power System Technology., Zhejiang, China, pp. 1-7 (2010).

[24] Larsson, M. and Karlsson, D. “Coordinated system protection scheme against voltage collapse using heuristic search and predictive control”, Int. J. IEEE Power Engineering Review., 22(6). pp. 59 – 59 (2002).

[25] Wen, J., Wu, Q., Turner, D. et al. “Optimal coordinated voltage control for power system voltage stability”, Int. J. IEEE Transactions on Power Systems., 19(2). pp. 1115-1122 (2004).

[26] Larsson, M. “A model-predictive approach to emergency voltage control in electrical power systems”, 43th IEEE. Conf. on Decision and Control (CDC), Nassau, Bahamas, (2004).

[27] Sun, X. and Zhang, W. “Coordinated optimal voltage control strategy in distribution networks with multi-microgrids,” IEEE. Conf. IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Kota Kinabalu, Malaysia, pp. 88-93 (2018).
[28] Jin, Li., Kumar, R. and Elia, N. “Security constrained emergency voltage stabilization: A Model Predictive Control based approach,” 47th IEEE. Conf. on Decision and Control., Cancun, Mexico, pp. 2469-2474 (2008).

[29] Li, Y., Hill, D. and Wu, T. “Nonlinear model predictive control with immune optimization for voltage security control,” 5th Int. Conf. Intelligent Control and Automation., Hangzhou, China, pp. 5189-5193 (2004).

[30] Zhang, F., Chan, K. W. and Fang, D. Z. “Optimal coordinated voltage emergency control against voltage collapse”, Int. J. of Electrical Power & Energy Systems., 53. pp. 442-449 (2013).

[31] Otomega, B., Glavic, M. and Van Cutsem, T. “A two-level emergency control scheme against power system voltage instability”, Int. J. Control Engineering Practice., 30. pp. 93-104 (2014).

[32] Negenborn, R., Leirens, S., De Schutter, B. et al. “Supervisory nonlinear MPC for emergency voltage control using pattern search”, Int. J. Control Engineering Practice., 7. pp. 841-848 (2002).

[33] Larsson, M., Hill, D. J. and Olsson, G. “Emergency voltage control using search and predictive control”, Int. J. of Electrical Power &Energy Systems. 24(2). pp. 121-130 (2002).

[34] Amraee, T., Ranjbar, A. and Feuillet, R. “Adaptive under-voltage load shedding scheme using model predictive control”, Int. J. of Electric Power Systems Research. 81(7), pp. 1507-1513 (2011).

[35] Pourjafari, E. and Mojallali, H. “Predictive control for voltage collapse avoidance using a modified discrete multi-valued PSO algorithm,” Int. J. ISA Transactions. 50(2). pp. 195–200 (2011).

[36] Ma, H., Man, K. and Hill, D.J. “A jumping genes scheme for multi-objective coordinated voltage control,” 4th Int. Conf. on Industrial Informatics, Singapore, (2006).

[37] Ma, H. M., Ng, K. T. and Man K. F. “Multiobjective coordinated power voltage control using jumping genes paradigm,” Int. J. IEEE Transactions on Industrial Electronics. 55(11). pp. 4075-4084 (2008).

[38] Ma, H. M., Ng, K. T. and Man K. F. “A multiple criteria decision-making knowledge-based scheme for real-time power voltage control,” Int. J. IEEE Transactions on on Industrial Informatics. 4(1). pp. 58-66 (2008).
[39] Ma, H. and Hill, D. J. “Adaptive coordinated voltage control—Part I: Basic scheme,” *Int. J. IEEE Transactions on Power Systems*. **29**(4), pp. 1546-1553 (2013).

[40] Ma, H. and Hill, D. J. “Adaptive coordinated voltage control—Part II: Use of learning for rapid desponse,” *Int. J. IEEE Transactions on Power Systems*. **29**(4), pp. 1554-1561 (2014).

[41] Karbalaei, F. and Shahbazi, H. “A quick method to solve the optimal coordinated voltage control problem based on reduction of system dimensions,” *Int. J. Electric Power Systems Research*. **142**, pp. 310-319 (2017).

[42] Islam, S. R., Muttaqi, K. M. and Sutanto, D. “A decentralized multiagent-based voltage control for catastrophic disturbances in a power system,” *Int. Conf. IEEE Industry Applications Society Annual Meeting.*, Lake Buena Vista, FL, USA, (2013).

[43] Zhao, B., Xu, Z., Xu, C. et al. “Network partition-based zonal voltage control for distribution networks with distributed PV systems” *Int. J. IEEE Transactions on Smart Grid.*, **9**(5). pp. 4087-4098 (2018).

[44] Islam, S. R., Sutanto, D. and Muttaqi, K. M. “Coordinated decentralized emergency voltage and reactive power control to prevent long-term voltage instability in a power system,” *Int. J. IEEE Transaction on Power Systems*. **30**(5), pp. 2591-2603 (2014).

[45] Shahbazi, H. and Karbalaei, F. “Decentralized Voltage Control of Power Systems Using Multi-Agent Systems,” *Int. J. of Modern Power Systems and Clean Energy.*, **8**(2), (2020).

[46] Ma, H. and Hill, D.J. “A Fast Local Search Scheme for Adaptive Coordinated Voltage Control”, *Int. J. IEEE Transaction on Power Systems*. **33**(3), pp. 2321-2330 (2018).

[47] Huang, Q., Huang, R., Hao, W. et al. “Adaptive power system emergency control using deep reinforcement learning,” *Int. J. IEEE Transactions on Smart Grid*. **11**(2), pp. 1171-1182 (2019).

[48] Liu, H., Su, J., Qi, J. et al. “Decentralized voltage and power control of multi-machine power systems with global asymptotic stability” *In. J. IEEE Access.*, **7**, pp. 14273-14282 (2019).

[49] Guzman, R., De Vicuna, L. G., Camacho, A. et al. “Receding-horizon model-predictive control for a three-phase VSI with an LCL filter”, *Int. J. IEEE Transactions on Industrial Electronics*. **66**(9), pp. 6671-6680 (2018).
[50] Jin, T., Shen, X., Su, T. et al. “Model predictive voltage control based on finite control set with computation time delay compensation for PV systems”, *Int. J. IEEE Transactions on Energy Conversion*. 34(1), pp. 330-338 (2018).

[51] Wu, F. F. and Monticelli, A. “Critical review of external network modelling for online security analysis,” *Int. J. of Electrical Power & Energy Systems*. 5(4), pp. 222-235 (1983).

[52] Mehrjerdi, H., Lefebvre, S., Asber, D. et al. “Graph partitioning of power network for emergency voltage control,” 9th *Int. Conf. Asian Control Conference (ASCC)*, Istanbul, Turkey, pp. 23-26 (2013).

[53] Alzaareer, K., Saad, M., Mehrjerdi, H. et al. “Development of new identification method for global group of controls for online coordinated voltage control in active distribution networks,” *Int. J. IEEE Transactions on Smart Grid*. 11(5), pp. 3921-3931 (2020).

[54] Hosseinnezhad, V., Rafiee, M., Ahmadian, M. et al. “Optimal island partitioning of smart distribution systems to improve system restoration under emergency conditions”, *Int. J. of Electrical Power & Energy Systems.*, 97. pp. 155 – 164 (2018).

Abbreviations:

OCVC: optimal coordinated voltage control

MPC: model predictive control
CVC: coordinated voltage control

PID: proportional integral derivative

PSO: particle swarm optimization

EMS: energy management system

OLTC: on-load tap changers

MCDM: multi-criteria decision making

Mandana Hojati Tabatabaie received the B.Sc. degree in Electronic Engineering from Islamic Azad University Garmsar Branch in 2008 and M.Sc. degree in Power Electrical Engineering from Imam Khomeini International University of Qazvin in 2012. She is currently PhD student in Power Electrical from Islamic Azad University-South Tehran Branch.

Hassan Siahkali (S'06) was born in Tehran, Iran, 1970. He received the B.Sc. degree in Electronic Engineering from the Tabriz University, Tabriz, Iran in 1993 and M.Sc. and PhD degrees both in Electrical Engineering from the Amir Kabir University of Technology and Sharif University of Technology, Tehran, Iran in 1997 and 2010, respectively. He worked as a project manager at the Niroo Research Institute (NRI) from 1999 to 2005. He is currently working with Islamic Azad University-South Tehran Branch as an assistant professor, since 2006. His main research interests are in the areas of electric power systems planning and operation and restructuring of power system.

Javad Olamaei (SM'18) received his B.Sc., M.Sc. and Ph.D. degrees in Electrical Engineering in 1988, 1992 and 2008 from Tabriz University, Tabriz, Iran and Amir Kabir University of Technology (AUT), Tehran, Iran and Islamic Azad University-Science and Research Branch, Tehran, Iran, respectively. He has been holding the Lecturer position from Jan. 1997 to June. 2009, the Assistant professor position from June. 2009 to Feb. 2018 and the associate professor position at Islamic Azad University-South Tehran Branch since Feb. 2018. He was the head manager of Islamic Azad University South Tehran Branch from 2018 to 2019. From 2019 till yet. He is the Deputy Minister of Science, Engineering and Agriculture of Islamic Azad University. He is the author of more than 100 international journal and conference papers. His teaching and research interest include Power Distribution Systems, Distribution Automation System, Micro grids, Renewable Energy and VAR Planning.

Figure and table captions

Figures:

Figure 1: Classification of papers dealing with emergency voltage control
Figure 2: The control structure of OCVC (optimal coordinated voltage control) based on MPC (model predictive control)

Figure 3: (A) Ward, (B) Ward-PV, (C) Modified Ward-PV model

Figure 4: Proposed algorithm to solve the OCVC (optimal coordinated voltage control) problem

Figure 5: Performance of the system after outage of the generator 32, without a control system

Figure 6: The set of non-dominated answers

Figure 7: Partitioning of power system for scenario I

Figure 8: Performance of control system with a reference voltage tracking approach

Figure 9: Performance of control system with reducing the control actions

Figure 10: Performance of system in scenario II, without a control system

Figure 11: System partitioning after fault in scenario II

Figure 12: Performance of control system through reference voltage tracking approach in scenario II

Figure 13: Performance of control system through reducing the control actions in scenario II

Figure 14: Performance of control system against consecutive faults in scenario III

Tables:

Table 1: Comparing papers of group (A) to (D)

Table 2: Set of non-dominated solutions

Table 3: Preference matrix

Table 4: Preference matrix

Table 5. A comparison between the performance of linearization method and Modified Ward-PV methods

Table 6: Number of System Equations in each Methods

Table 7: Comparison of performance two methods of linearization and Modified Ward-PV in scenario II

Table 8: Number of system equations in each method based on scenario II

Table 9: The number of control actions and load shedding steps in scenario III
Figures and Tables:
Emergency Voltage Control

Multi-area System

Single-area System

Decentralized Voltage Control (Group A)

Single Objective Optimization (Group B)

Coordinated Voltage Control based on MPC

Complete Model (Group C)

Multi-objective Optimization

Reduced Model (Group D)

Figure 1. Classification of papers dealing with emergency voltage control

Figure 2. The control structure of OCVC (optimal coordinated voltage control) based on MPC (model predictive control)
Figure 3. (A) Ward, (B) Ward-PV, (C) Modified Ward-PV model
Figure 4. Proposed algorithm to solve the OCVC (optimal coordinated voltage control) problem
Figure 5. Performance of the system after outage of the generator 32, without a control system

Figure 6. The set of non-dominated answers
Figure 7. Partitioning of power system for scenario I
Figure 8. Performance of control system with a reference voltage tracking approach
Figure 9. Performance of control system with reducing the control actions

Figure 10. Performance of system in scenario II, without a control system
Figure 11. System partitioning after fault in scenario II

Figure 1. Performance of control system through reference voltage tracking approach in scenario II
Figure 13. Performance of control system through reducing the control actions in scenario II

Figure 14. Performance of control system against consecutive faults in scenario III
Tables:

### Table 1. Comparing papers of group (A) to (D)

| Description | Group (A) | Group (B) | Group (C) | Group (D) |
|-------------|-----------|-----------|-----------|-----------|
| Consider all constraints | ✓ | ✓ | ✓ | ✓ |
| Adaptive method | ✓ | ✓ | ✓ | ✓ |
| Optimal Method | × | ✓ | ✓ | ✓ |
| Minimum load shedding | × | × | ✓ | ✓ |
| Flexibility method | × | × | ✓ | ✓ |
| Good performance against unanticipated fault | ✓ | × | × | ✓ |
| Good performance against consecutive faults | ✓ | ✓ | ✓ | ✓ |
| Speed of solving problem | High | Low | Low | High |
| Applied in large power system | ✓ | × | × | ✓ |

(1) This depends on the objective function (Tracing reference voltage / Minimizing number of control actions / Minimizing load shedding).

### Table 2. Set of non-dominated solutions

| | $f_1 = \sum v_i$ | $f_2 = J_{act}$ | $f_3 = J_{load}$ |
|---|---|---|---|
| $A_1$ | $a_{11}$ | $a_{12}$ | $a_{13}$ |
| $A_2$ | $a_{21}$ | $a_{22}$ | $a_{23}$ |
| ... | ... | ... | ... |
| $A_i$ | $a_{i1}$ | $a_{i2}$ | $a_{i3}$ |
| ... | ... | ... | ... |
| $A_n$ | $a_{n1}$ | $a_{n2}$ | $a_{n3}$ |

### Table 3. Preference matrix

| | $f_1 = \sum v_i$ | $f_2 = J_{act}$ | $f_3 = J_{load}$ |
|---|---|---|---|
| $f_1 = \sum v_i$ | $m_{11}$ | $m_{12}$ | $m_{13}$ |
| $f_2 = J_{act}$ | $m_{21}$ | $m_{22}$ | $m_{23}$ |
| $f_3 = J_{load}$ | $m_{31}$ | $m_{32}$ | $m_{33}$ |
### Table 4. Preference matrix

| 1. Tracing reference voltage | 2. Economic consideration |
|------------------------------|---------------------------|
| $f_1 = \sum vi$ | $f_1 = \sum vi$ |
| $f_2 = J_{act}$ | $f_2 = J_{act}$ |
| $f_3 = J_{load}$ | $f_3 = J_{load}$ |

### Table 5. A comparison between the performance of linearization method and Modified Ward-PV methods

| Method                              | Time for each Local Search (s) | Tracing Reference Voltage | Number of Control Actions |
|-------------------------------------|---------------------------------|---------------------------|---------------------------|
|                                     |                                 | f_1 | f_2 | f_3 | f_1 | f_2 | f_3 |
| Reduced based on Linearization Method | 8.5                            | 1.98 | 24  | 0   | 1.73| 11  | 0   |
| Reduced based on Modified Ward-PV Method | 11.4                           | 0.91 | 23  | 0   | 0.84| 11  | 0   |

### Table 6. Number of System Equations in each Method

| Method                              | Number of Equations After Fault Occurrence | Number of Equations Before Fault Occurrence |
|-------------------------------------|--------------------------------------------|---------------------------------------------|
| Non-reduced Model                   | 190                                        | 190                                         |
| Reduced based on Linearization Method | 79                                         | 66                                          |
| Reduced based on Modified Ward-PV Method | 139                                       | 137                                         |

### Table 7. Comparison of performance two methods of linearization and Modified Ward-PV in scenario II

| Method                              | Time for each Local Search (s) | Tracing Reference Voltage | Number of Control Actions |
|-------------------------------------|---------------------------------|---------------------------|---------------------------|
|                                     |                                 | f_1 | f_2 | f_3 | f_1 | f_2 | f_3 |
| Reduced based on Linearization Method | 8.2                            | 3.1  | 31  | 3   | 1.93| 14  | 2   |
| Reduced based on Modified Ward-PV Method | 11.2                           | 1.3  | 29  | 4   | 0.9 | 13  | 2   |
Table 8. Number of system equations in each method based on scenario II

| Method                           | Number of Equations After Fault Occurrence |
|----------------------------------|--------------------------------------------|
| Non-reduced Model                | 190                                        |
| Reduced based on Linearization Method | 70                                         |
| Reduced based on Modified Ward-PV Method | 136                                       |

Table 9. The number of control actions and load shedding steps in scenario III

| Method                           | $f_2$ | $f_3$ |
|----------------------------------|-------|-------|
| Faults at t=30s and 75s          | 25    | 3     |
| Faults at t=30 and 105s          | 24    | 4     |