A New Framework for Congestion Management with Exact Modeling of Impacting Factors

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Abstract: Congestion in the transmission lines is one of the technical problems that appear particularly in the deregulated environment. The voltage stability issue gets more important due to heavy loading in this environment. The main factor causing instability is the inability of the power system to meet the demand for reactive power. This paper presents a new approach for alleviation congestion relieving cost by feeding required reactive power of system in addition to re-dispatching active power of generators and load shedding. Furthermore with considering different static load models in congestion management problem with both thermal and voltage instability criteria, tries to the evaluated congestion management cost become more real, accurate and acceptable. The voltage stability is a dynamic phenomenon but often static tools are used for investigating the stability conditions, so this work offers new method that considers two snapshots after contingency to consider voltage stability phenomena more accurate. This algorithm uses different preventive and corrective actions to improve unsuitable voltage stability margin after contingency. The proposed method is tested on IEEE 24-bus Reliability test system, the simulation results shows the effectiveness of the method.

Keywords: Congestion Management, Corrective Actions, Preventive, Static Load Models, Voltage Stability.

1 Introduction

In deregulated power systems, market can reduce efficiently the cost and maximize social welfare, but on the other hand it causes transmission congestion since the power system running closely to its limit aimed to get more economy benefit. In this environment a system is said to be congested when some specified operating constraints (e.g., branch current, bus voltage magnitude, etc.) or security constraints (e.g., thermal, voltage stability, angle stability, etc.) are violated in the current or in a foreseen operating state [1]. Open access implies that the opportunities of using the transmission system must be equally available to all buyers and sellers. The aim is to remove or reduce the physical limitations of the free trade, which cause network zones with significantly different prices. The methods to relief congestions can be divided into two main categories [1]; economical (e.g., market splitting, auctioning) and technical (e.g., generation re-dispatch, transactions curtailment). The approaches considered in this study fall in the second category.

Traditional congestion management paid lots of attentions to constrains of line transmission capability [2-14], but voltage stability is one of major constraints affecting security of power system. Voltage stability problems often occur in heavily loaded systems. So management of the congestion due to voltage stability is too important in foreseen operating states (established after the day-ahead market clearing). In recent years voltage stability is paid much more attention under electric market environment [1, 15-22].

One of the congestion management methods is using of FACTs devices that with changing the lines parameters provide effective usage of transmission line capacity [2-7]. In some literature [8, 10, 21, 22], by cutting the some transactions that cause congestion, try to reduce overloading of the lines. This means load-shedding is one of the congestion relief methods.

Optimal power flow (OPF) is the most significant technique for congestion management in a power system with existing transmission and operational constraints [2, 10, 21]. The OPF uses control variables like active and reactive generation powers to achieve a good tradeoff between security and economics. More specifically, OPF program optimizes the power system

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operating condition with respect to a pre-specified objective (minimum operating cost, maximum power flow), while respecting generator limits and static security constraints (line power flows and bus voltage limits) [11].

A congestion clusters based method, which identifies the group of system users according to their impact on transmission constraints of interest, has been proposed in [12-14]. The transmission congestion distribution factors (TCDFs) based on AC load flow Jacobian sensitivity [12, 13] and DC load flow [14] has been proposed for identifying the buses that increment or decrement of their output more decrease overloading of lines. Literatures [16-21] consider minimum load margin as voltage stability constraint in voltage stability constrained-OPF (VSC-OPF) under normal and contingency conditions where generation rescheduling and load shedding are proposed as solution of reliving congestion due to voltage stability.

There are some useful methods for estimating steady-state voltage stability [15] such as sensitivity analysis, modal analysis and load margin method. Load margin reflects the distance of the currently operation point to voltage collapse point, with which the system can be indicated to be stable or not. The expanded modal analysis [22-25] technique allows the best choice of control actions to get over congestion problems, such as the identification of key areas for interruptible load incentives, the best generator re-dispatch scheme for eliminating congestion, critical areas for investment on reactive power ancillary services and others.

Da Silva at [22] applied Active Participation Factor (APF) to identify those buses where active power changes are more detrimental to system voltage stability. He uses active power based control actions, such as load shedding and generator rescheduling, for improving voltage stability margin (VSM) and didn't consider thermal overload criteria in his work.

Geo [24] defines the Reactive Participation Factor (RPF) from the reactive power reduced matrix JRQV, which related to the reactive power demand at load (PQ) buses, and indicates the best location for reactive power compensation based control actions. In this work RPF is interested. Capitanescu at [1] proposes two approaches for management of congestions due to voltage instability and thermal overload in a deregulated environment. The first approach, referred to as Injection Control (IC), relies on power injections, i.e., generator productions and load consumptions. The second approach, referred to as Transaction Control (TC), relies on power transactions. The IC approach can be implemented in any deregulated model. It consists of modifying the market-based generation scheme at the least cost, according to the generators' bids. But the TC approach can just applied in deregulated systems operated under the bilateral contract model [1]. It consists of curtailing non-firm transactions in some optimal manner in order to relieve congestions.

Up to now, both thermal overload and voltage stability have been considered in congestion management problems [16-19], but they have been solved inadequate VSM problem in different contingencies, only with changing "active" power of generators and loads. It means in an optimal manner, active power of generators and loads were been adjusted to maintain desired load margin for all single contingencies and in order to relieve congestion and in objective function just the cost of active powers changes have been tried to minimize. Those methods impose high cost to market participants and since generation and consumption of players must be adjusted to cover all single contingencies, the competitive operation of the market would be affected. So, since the main factor causing instability is the inability of the power system to meet the demand for reactive power [28], we have tried to improve voltage stability of the system and decrease reactive flow of branches, firstly by providing required reactive power of the system locally (setting value of reference voltage of PVs, tap changer adjustments, capacitor placement, etc.) and if had not been satisfied enough load margin, we suggested finally the operation of phase shifting transformers, generation rescheduling and loads shedding to relieve congestions. Due to lower cost of reactive power rather than the active one, the proposed method will impose lower cost on market participations as congestion management cost.

On the other hand, stable operation of a power system depends on the ability to continuously match the electrical output of generating units to the electrical load on the system. Consequently, load characteristics have an important influence on system stability [28]. Hence one of the important issues on voltage stability and thermal security is how to model the loads in the system while the previous congestion management works paid no attention to it and they have just considered PQ constant model of load. Here, we have shown the effect of considering other static load models on congestion management cost and voltage stability margin and also have been attempted to consider general static load model that commonly uses for loads.

This work is also interested in the study of voltage stability condition at different snapshots of system after single contingency; when some controllers have responded and some other not, and the goal is to present suitable preventive or corrective actions to ensure required margin at different situations is available and the system is protected from unpredictable voltage collapse.

Briefly, this work presents three main contributions as follow:

1. Consideration of four static load models in congestion management problem to show their effectiveness on cost and voltage stability margin and on RPFs for capacitor placement.

2. Presenting a new method for simulating the system conditions at two snapshots after contingency

for considering more exact model of voltage stability phenomenon and propose an algorithm that uses different preventive and corrective actions to improve unsuitable voltage stability margin after contingency.

3. Applying reactive power based control actions in addition to active power based control actions for decreasing congestion management cost and improving VSM more effectively.

The paper is organized as follows. Section 2 presents Reactive Participation Factor based on Modal analysis. The proposed algorithm presented in Sections 3. Section 4 offers some numerical results with the proposed methods while some conclusions are drawn in Section 5.

2 Reactive Participation Factors (RPF)

The linearized power flow equations can be formulized as follows [22-25]:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} = J \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \tag{1}$$

where JPθ, JPV, JVθ and JQV are Jacobian sub-matrices representing the sensitivities of active and reactive power with respect to voltage angles and magnitudes. J is the standard load flow Jacobian matrix. Two reduced Jacobian matrices can be defined as:

$$\Delta V = J_{RQV}^{-1}\Delta Q \text{ , by assuming } \Delta P=0 \tag{2}$$

$$\Delta\theta = J_{RP\theta}^{-1}\Delta P \text{ , by assuming } \Delta Q=0 \tag{3}$$

where,

$$J_{RQV} = J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV} \tag{4}$$

$$J_{RP\theta} = J_{P\theta} - J_{PV} J_{QV}^{-1} J_{Q\theta} \tag{5}$$

The reduced matrices JRQV and JRPθ represent the sensitivities of system equilibrium with respect to reactive and active power incremental variations. Information about system voltage stability can be obtained from these matrices in both perspectives: reactive and active power conditions.

Modal analysis applied to reduced or unreduced Jacobian matrices results in [22]:

$$J = \Phi.\Lambda.\Gamma \tag{6}$$

where:

Φ - Contain the right eigenvectors of matrix J;

Γ - Contain the left eigenvectors of matrix J;

Λ - Contain the eigenvalues of matrix J.

Gao[24] defines the Reactive Participation Factor (RPF) from the reactive power reduced matrix JRQV, and Da Silva [22] defines the Active Participation Factor from active power reduced matrix JRPθ.

The RPF is defined as the element by- element product of the left and right eigenvectors of the JRQV matrix. If λ_i is the *i*-th eigenvalue of JRQV, and μ_i and ν_i its right and left eigenvectors related to λ_i, the participation factor of bus *k* to mode *i* is defined as [24]:

$$RPF_{ki} = \mu_{ik} \nu_{ki} \tag{7}$$

The RPF reveals those buses where reactive power changes are more detrimental to system voltage stability. The RPF is related to the reactive power demand at load (PQ) buses, and indicates the best locations for reactive power compensation based control actions.

3 Proposed Algorithm

This paper considers a day-ahead electricity energy market based on a pool mechanism. More often than not, pool market results originate network congestion problems, and the independent system operator (ISO) should determine the minimal changes in the market results that ensure a secure operation. So after the market-clearing procedure –with the goal of maximizing social welfare- congestion management program runs for hour by hour of network with market clearing procedure results in 24 hours of next day and the result of congestion management (congestion relieving actions) announces to producers and customers by ISO.

As power systems are increasingly operating under heavy loads, voltage stability becomes a critical concern. When the voltage in the system is uncontrollable and continuously decreases due to failures in the design, external factors, variations in load or inappropriate voltage control devices, the system becomes unstable and enters in the stage of voltage instability. The main reason to lead a power system to an unstable situation and consequently to instability, is the incapacity of satisfying the reactive load demand under heavily stressed conditions, to keep voltage at acceptable levels. Voltage collapse follows voltage instability, and it is often the result of the action of voltage control devices, load tap changers, the voltage dependence characteristic of the load, the generator reactive power limits or the combination of several of them [29]. Voltage collapse leads the system to low-voltage values in a large part of the power system, and therefore to partial or total collapse.

Since long term voltage instability that causes slow voltage collapse is directly related to power system loadability, one of the concerns of system operator is to increase system loadability. The WSCC voltage stability criteria are specified in terms of real and reactive power margins for kinds of contingencies. The operator of system must provide the minimum margins specified in [8]. The margin for base case conditions also must be adequate to allow for unforeseen increases in load or interface flows without remedial action schemes (which would be activated during contingency conditions but not during normal conditions).

The system shows a dynamic behavior against voltage stability phenomenon in the present of time dependent responsive devices in the system (e.g., generators excitation limiters, OLTC, switching capacitors, SVC and etc.) which response at different times in range of 1 second till 10 minutes after a disturbance. Fig. 1 shows the time that different controllers response [31].

To correctly analyze the voltage stability of a power system, suitable dynamic models are usually required based on nonlinear differential and algebraic equations. However, in many cases, static analysis tools are used to estimate stability margins, because being easy to model and computation speed. One of methods for considering influence of different controller reactions on the system against a disturbance, is to snapshoot the system at different time situations, when different components, devices, and controls response. And the study of these snapshots is equal to study dynamic behavior of the system and recognizing the suitable preventive or corrective actions, would be possible.

We choose two snapshots to model the system more accurate after a disturbance and calculate the cost of congestion relief more real and reasonable:

First one, immediately after contingency when no controllers has not yet responded, if one of contingencies cause insufficient voltage stability margin (VSM>0 is enough for this time), this problem must be solved by preventive controls, it means minimum required VSM for this contingency must be considered as a criterion in the optimization problem to force the system readjust and overlap that contingency.

The second snapshot is after reaction of all controllers and other system responsive devices, means about 10 minutes after single contingency. In this situation, system operator recognizes those contingencies that won't satisfy required VSM according to WSCC [8]. Since reaction of some devices like tap changers and some controllers like generators limiters will destroy the margin of system, it's necessary to ensure the value of VSM is adequate (according to WSCC, load margin must be greater than or equal to 5 percent for all single contingencies). Fortunately, in this snapshot there is enough time to apply corrective controls like dynamic reactive power sources, and it's possible to improve margin by corrective actions which would be activated during contingency conditions but not during normal conditions. And the corrective congestion cost is needed to pay only after that specific contingency actually occurs.

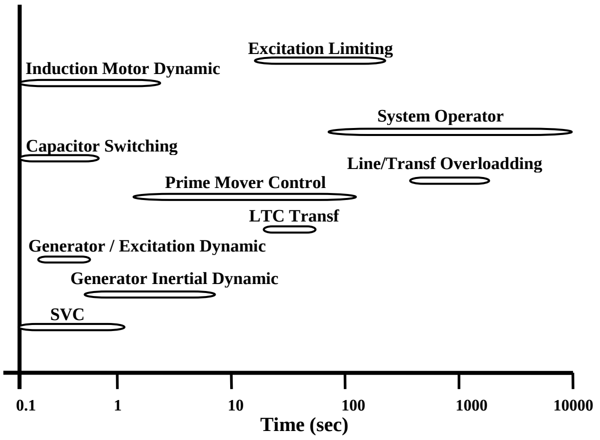


Fig. 1. The response time of different controllers in power system.

Dynamic reactive power sources include generators, synchronous condensers, static VAR controllers, etc. Static sources include capacitors or similar sources of reactive power. And the Reactive Participation Factor (RPF) - described in section 2- which related to the reactive power demand at load (PQ) buses, can be used to indicate the critical areas for investment on reactive power ancillary services to improve system stability in optimization problem and at second snapshot.

Single contingency is the outage of one system element. System elements include any facility, such as a generator, transmission line, transformer, reactive power source, etc. (simply, only outage of transmission line and transformer are considered in case study, excluded the one that made the system into islands).

The purpose of congestion management, is to find the optimal settings of a given power system network that optimize a certain objective function while satisfying its power flow equations, system security, equipment operating limits and minimum stability margin. The levels of security which should be considered in market clearing or congestion management is very important not only for secure operation of power system, but also for market participants [19]. The higher the level of security is, the higher the congestion cost is. And the more social welfare is lost. Therefore in operation of power system, a compromise must be made between the level of security and economic interests of market participants. As a guideline for operation of power system, WSCC (Western Systems Coordinating Council) specified minimum loading margin under different operating conditions in [8].

Different control variables are manipulated to achieve an optimal network setting based on the problem formulation. The main control variables used in this optimization are as follows:

- Generators' real power outputs and voltages.
- Transformer tap changing settings.
- Phase shifters settings.
- Switched capacitors and reactors.
- And the active and reactive power of loads.

The proposed congestion management program combining the following two objectives:

(i) Minimizing the cost of congestion management by applying reactive power sources.

(ii) Improving the voltage stability margin (VSM) of system at normal operating conditions.

The objective function of problem is:

$$Min:\{\ k_1[\text{cost}(\Delta Q_{sh})+\text{cost}(\Delta Q_g)+\text{cost}(\Delta P_g)+\text{cost}(\Delta P_l)+\text{cost}(\Delta Q_l)]-k_2(VSM_n)\ \}\quad(8)$$

where,

ΔQ_{sh}: the changes of reactive power produced by shunt capacitors.

ΔQ_g: the changes of reactive power produced by synchronous machines.

$\Delta P_g = P_g - P_{g0}$: the changes of active power produced by generators. P_{g0} is output of market clearing procedure.

$\Delta P_L = P_L - P_{L0}$ changes of active power consumed by loads. PL0 is output of market clearing procedure.

$\Delta Q_L = Q_L - Q_{L0}$ changes of reactive power consumed by loads.

Q_{L0} is initial reactive power according to P_{L0}.

VSM_n: the voltage stability margin at normal condition.

$k_{1,2}$: the weighting factors. With adjusting these factors we can tradeoff between minimizing the cost and maximizing the voltage stability margin of system.

The constraints of problem are:

- The power flow equations
- The inequality constraint on real power generations
- The inequality constraint on real power loads
- The inequality constraint on reactive power generation at PV buses
- The inequality constraint on voltage of PQ buses
- Appearance power limit on branches (transmission lines and transformers)
- Minimum values of VSM immediately after critical contingencies (that must be greater than zero).

These constraints appear at objective function as a penalty factor and minimizing this penalty factor means bring constraints violated from their boundary, to their limits.

This work uses reactive power based control actions (e.g., PVs voltage setting, Transformers tap changing setting and capacitor banks) in addition to active power based control actions (e.g., real power of generators, phase shifters setting and load shedding) as optimization control parameters and try to relieve congestion due to voltage instability and thermal overload of system. While previous works in the field of congestion management ensuring voltage stability, just applied generators rescheduling and load shedding as solution (we called classical method). Since the reactive power cost is less than the active one and the load shedding imposes high cost, the proposed solution would be cheaper than the classical method.

We solved the mentioned optimization problem by both classical and proposed control variables to show the effectiveness of the new method. In classical method just by re-dispatching of generators and shedding of loads- we called them classical control variables-, have tried to solve the congestion problem. So our objective function would change with classical control variables and would be:

$$Min:\{\ k_1[\text{cost}(\Delta P_g)+\text{cost}(\Delta P_l)+\text{cost}(\Delta Q_l)]-k_2(VSM_n)\ \}\quad(9)$$

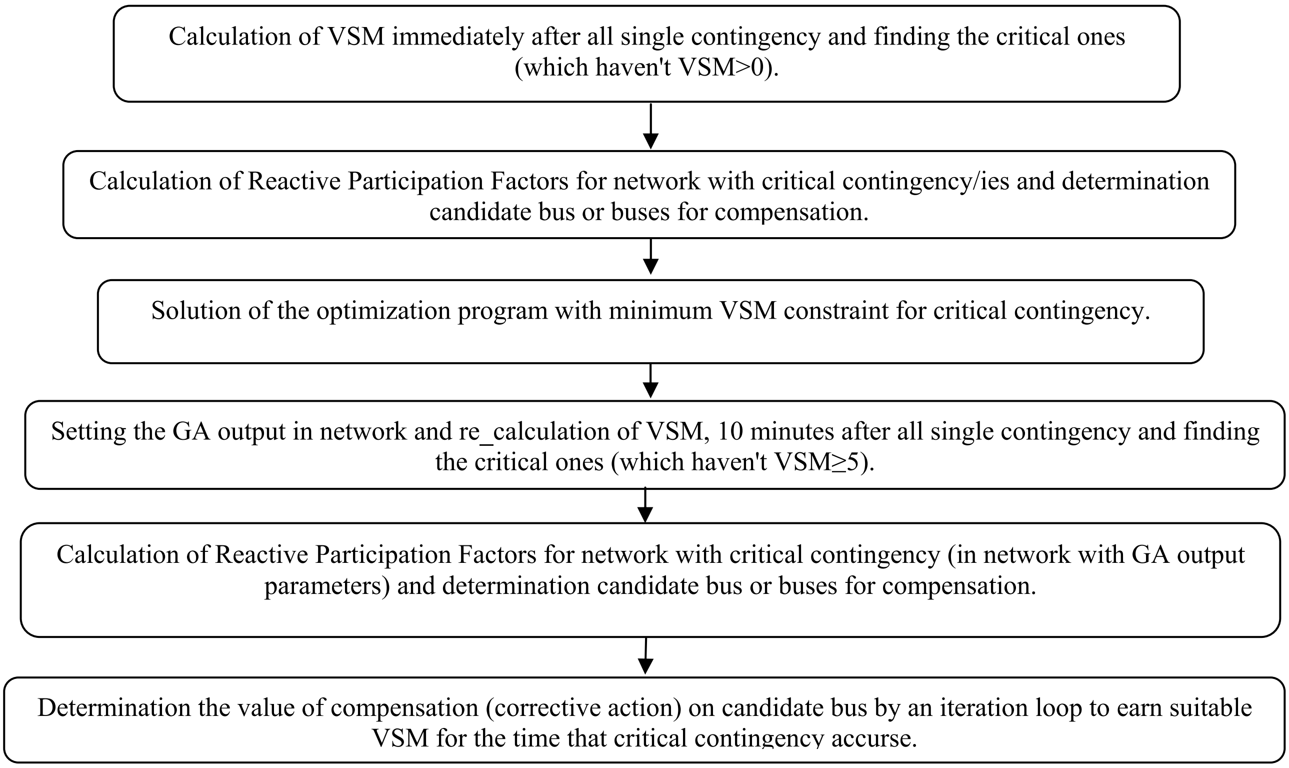
In congestion management problems the objective function and constraints are nonlinear and non-convex [2]. To solve such equations classical techniques offer good results but when the search space is nonlinear and has discontinues these techniques become difficult to solve with a slow convergence ratio not always seeking to the optimal solution. New numerical methods have been successfully applied to a wide range of optimization problems in which global solutions are more preferred than local ones or when the problem has non-differentiable regions. Also, they are known for their capabilities of fast search of large solution spaces and their ability to account for uncertainty in some parts of the power system networks [32].

Recently a great deal of interest in promising genetic algorithm and its application to various disciplines including power system planning operation and control. Genetic algorithms are also being applied to a wide range of optimization and learning problems in many domains [2].

We used GA to solve our optimization problem and also Continuation Power Flow (CPF) to evaluate voltage stability margin of system for each chromosome (control parameters are the genes of each chromosome). Continuation methods [28, 30] are based on the power flow equations of the system, looking for the load that leads the system out of its feasible operational region. The method consists on following the solution path from a base case to a loadability limit, taking into account that the path folds at the limit point.

In this paper we applied reactive power based control actions in addition to active power based control actions to help the reliving the overload of branches and improving the stability margin. In the deregulated environment, reactive power is becoming more and more important especially from the view of security and the economic caused by it. A good allocation method should give a strong economic signal for the investor and operator of the power system, especially the producer of the electric power. About the reactive power pricing there are different methods [33-42], we would like to emphasize that this paper focuses on congestion management, not on reactive power pricing scenario, hence we use conventional method employed in power systems for pricing of reactive power of generators [38] and the capital investment return method for static compensators [42] (see appendix A).

Load characteristics have an important influence on system stability [28]. The load characteristic and its dynamics indicate the dependency between the load and the voltage, and therefore the close coupling with the voltage stability phenomenon. A voltage drop will initially result in decay in load, but after few seconds, a



Calculation of VSM immediately after all single contingency and finding the critical ones (which haven't VSM>0).

Calculation of Reactive Participation Factors for network with critical contingency/ies and determination candidate bus or buses for compensation.

Solution of the optimization program with minimum VSM constraint for critical contingency.

Setting the GA output in network and re_calculation of VSM, 10 minutes after all single contingency and finding the critical ones (which haven't VSM≥5).

Calculation of Reactive Participation Factors for network with critical contingency (in network with GA output parameters) and determination candidate bus or buses for compensation.

Determination the value of compensation (corrective action) on candidate bus by an iteration loop to earn suitable VSM for the time that critical contingency accurse.

Fig. 2. The flow chart of proposed algorithm

load restoration process will start. The restoration can lead to heavily loaded conditions, and to voltage instability and voltage collapse if under those conditions, appropriate control decisions are not taken, and/or the system is not able to meet the reactive load demand [29]. As another contribution, we considered different static load models (constant power, constant current and constant impedance) which are described in [26-29]. Also, the result of congestion management in a system with a general static load model -that commonly uses for power system loads- is presented. In this model, real part of loads is considered as constant current load and the imaginary part of loads is considered as constant impedance load. So we can show how the different static loads can affect the stability, the amount of branches overload and the congestion management costs. The flow chart of proposed algorithm is shown in Fig. 2.

4 Case Study and Numerical Results

To test the proposed algorithm, the IEEE-24 Bus Reliability Test System was employed. A single line diagram is depicted in Fig. 3, which consists of 11 synchronous machines including one synchronous compensator at bus 14 and others are generators.

The bus and branch data of the system can be obtained from [43]. The base active and reactive loads, as well as the active power generated are shown in Tables B.1, B.2 respectively, in the appendix B. Thermal capacity limits of the lines are also given in [43]. The capacity limit of line 14-16 is reduced to 270 MVA in this paper (instead of 500 MVA) so that congestion occurs [16]. Generator and demand data are given in the [15]. In [15] has been noted that the price bids by generators and demand values have been selected arbitrarily close to the corresponding marginal cost values and considering adjusting up slightly more expensive than adjusting down for generators and the opposite for demands.

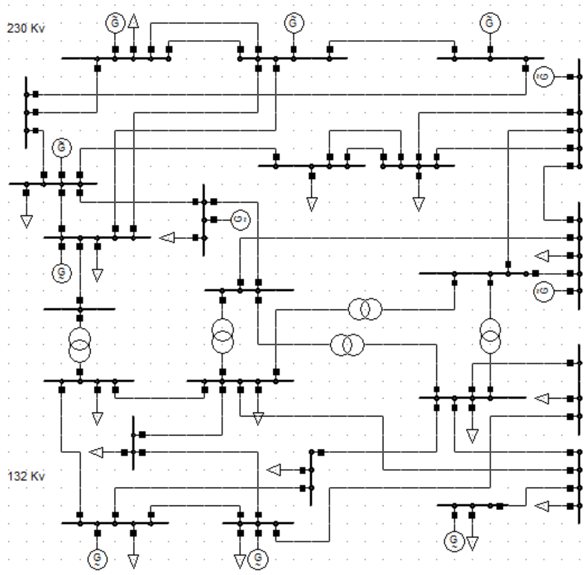


Fig. 3. single line diagram of IEEE 24-bus RTS.

Table 1 GA parameters

Parameter	Value
Population size	150
Mutation rate	0.05
Crossover rate	0.7
Crossover operator	Single point
Selection operator	Best sorted
Stop condition	20 similar iterations

We solved the optimization problems Eq. (8) and Eq. (9) respectively by classical and proposed control variables to show the effectiveness of the new method for different static load models. As it mentioned in section 3, we applied GA to solve our optimization problem. The control parameters are the genes of each chromosome and we calculated CPF to evaluate voltage stability margin of system and also cost of congestion management according to Eq. (8) and Eq. (9) for each chromosome.

We developed the GA program in MATLAB 7.8 (R2009a) [45] environment and for continuation power flow (CPF), we used the power system analysis toolbox (PSAT 2.1.6) software package [44]. PSAT is a MATLAB toolbox for electric power system analysis and simulation. The implemented GA parameters are given in Table 1.

For improving the stability margin by preventive action at the time situation of immediately after contingency, we need reactive power sources like shunt capacitor at suitable bus in the system. For this purpose, the Reactive Participation Factors (RPF) is calculated for all load buses immediately after critical contingency. Fig. 4 shows the RPFs for the critical mode in system with three different load models and Fig. 5 also shows the RPFs for general model of loads. This figures shows that the suitable buses for reactive power compensation are 5, 24 for constant power, bus number 5, 10 for constant current, 5, 6 for constant impedance load model and bus number 5, 8 for the 4th presented load model.

The simulation results including the value of objective functions and value of control variables of GA are shown in Tables 2, 3 respectively. In Table 2 we can see the result of simulation for different static load models (constant power, constant current, constant impedance and common load model). For comparing and showing the effectiveness of proposed method we solve the congestion management problem twice for each load models; once just with active power based control actions and another time with both active and reactive power based control actions. In column 3 the improvement of voltage stability margin for different

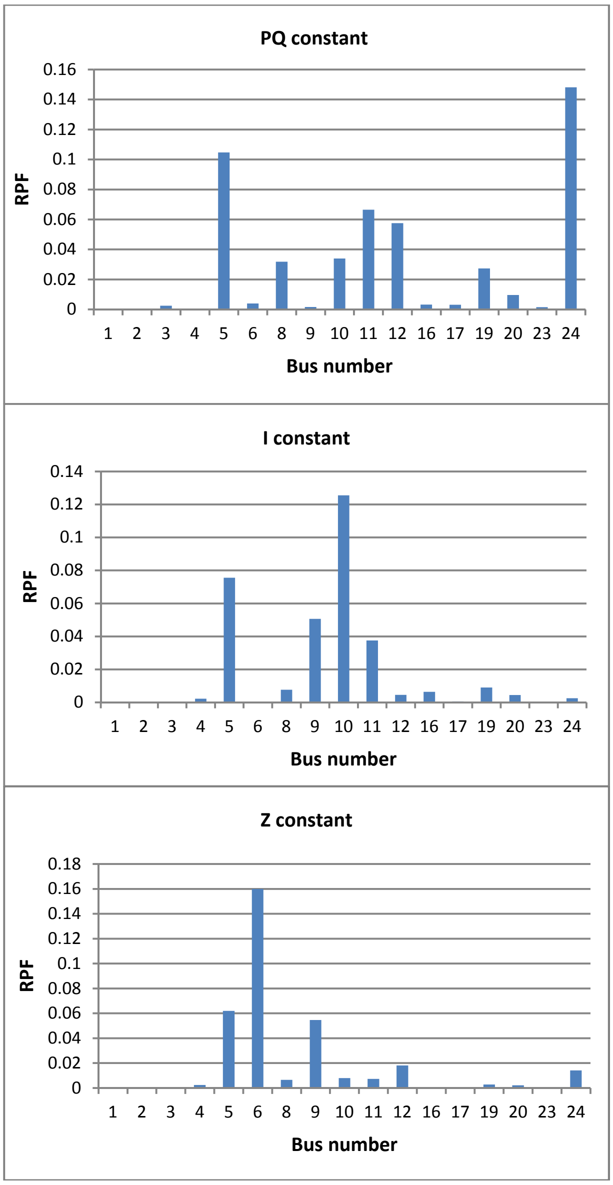


Fig. 4. Reactive Participation Factors for the critical mode in system with three different load models.

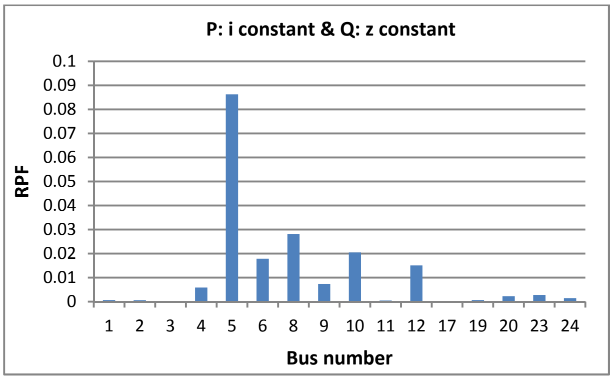


Fig. 5. Reactive Participation Factors for the critical mode in system with common load model.

Table 2 The simulation results for different kinds of loads

Load type	Control Variables	Improvement of VSM (%)	Congestion management cost include preventive actions cost ($/h)	Corrective actions cost paid to reactive source ($/h)
PQ constant load*	Classical (Just Active power)	-3.09	6000.81	_
	Proposed (Active & Reactive power)	5.71	3896.15	6.56
I constant load	Classical (Just Active power)	2.78	4233.05	_
	Proposed (Active & Reactive power)	3.24	2619.38	7.17
Z constant load	Classical (Just Active power)	3.77	3215.13	_
	Proposed (Active & Reactive power)	6.49	2533.88	1.99
I constant model for Active power of load & Z constant model for Reactive power of load**	Classical (Just Active power)	3.01	5689.95	_
	Proposed (Active & Reactive power)	4.11	3198.77	3.71

*base case of test systems **common load model

methods are shown. Column 4 shows the congestion management cost, including preventive control actions cost for improving the stability margin of critical contingencies that cause inadequate margin immediately after accurse (the identity of these preventive actions can be active or reactive power or both). Column 5 shows the cost of corrective reactive control actions for 10 minutes after contingency to increase the VSM to secure margin, for different kinds of loads, after setting the GA output parameters in the system, we calculated VSMs after all single contingency, and according to WSCC, load margin must be greater than or equal to 5 percent for single contingencies. This way we found the worst contingencies and applying RPF for these contingencies we indicated the suitable buses for reactive compensation. The simulation results suggest 1.11 pu shunt capacitor at bus 6 for system with constant power loads, 1.22 pu shunt capacitor at bus 6 for system with constant current loads, 0.34 pu shunt reactor at bus 12 for system with constant impedance loads and 0.63 pu shunt capacitor for system with common load model.

In Table 2 we can see these following results:

Congestion management cost (column 4) decrease from constant power to constant impedance load model, in both classical and proposed methods. This shows how much the different loads can affect the cost of congestion management that must pay by market participators. So if the loads in a power system don't model correctly, the calculated congestion management cost wouldn't be true and exact.

At any of four static load models, with comparing two classical and proposed methods, we can see significantly the effectiveness of reactive power control parameters on decreasing of congestion management costs. The value of this decrease is 35% for constant power, 38% for constant current, 21.2% for constant impedance and for 4th model of load the decrease value is 43.7%.

The proposed method (active and reactive power based control actions) can improve the margin of stability more significant than the classical one.

In system with PQ constant load model just by active power based control actions (classical method), we can't improve the VSM with a reasonable cost during congestion reliving process. As Table 3 shows, even with spending 6000.81 dollars as congestion reliving cost, the VSM is gotten worse and decreased by 3.09%.

In Table 3, the control variables which are the output of genetic algorithm program for proposed method are shown. These control parameters are respectively, voltage setting of PV buses, the changes of active power of generators, the changes of loads, the setting of tap changers, the value of shunt capacitors at buses that indicated at Figs. 4, 5 and the phase shifter setting at line 10-11. In this table, it's considered that when we solve the congestion management problem with new method, when loads of system model with constant power load model without load shedding we can't satisfy both objective functions by a reasonable cost, but about three other load models without use of load shedding we can reach to a suitable optimum point. This subject depicts that if the voltage dependency of loads becomes more, the requirement for load shedding becomes less. Therefore the initial market output would change less which is desired for market players.

5 Conclusions

This paper proposed a new method for congestion management with more exact modeling of impacting factors. The results show the role of reactive power in

Table 3 The value of control variables (GA output) for different static load models.

Control variable	**PQ constant load**	**I constant load**	**Z constant load**	**General model for load**
Vset at bus 13 (pu)	1.008	1.019	1.015	1.048
Vset at bus 1 (pu)	1.006	1.015	0.977	1.043
Vset at bus 2 (pu)	0.986	0.953	0.971	0.996
Vset at bus 7 (pu)	1.027	0.979	0.989	1.040
Vset at bus 14 (pu)	1.000	0.953	0.990	0.988
Vset at bus 15 (pu)	1.026	1.039	0.981	1.010
Vset at bus 16 (pu)	1.004	1.002	1.019	1.006
Vset at bus 18 (pu)	1.029	1.021	1.049	1.034
Vset at bus 21 (pu)	0.986	1.039	0.986	0.978
Vset at bus 22 (pu)	1.016	0.953	1.047	1.016
Vset at bus 23 (pu)	1.008	1.032	1.041	1.010
ΔPg at bus 1 (pu)	-0.057	0.000	0.000	0
ΔPg at bus 2 (pu)	0.024	-0.105	-0.144	-0.058
ΔPg at bus 7 (pu)	0.020	0.048	0.036	-0.05
ΔPg at bus 15 (pu)	-0.038	-0.042	-0.030	-0.097
ΔPg at bus 16 (pu)	-0.055	0.000	-0.126	-0.124
ΔPg at bus 18 (pu)	-0.164	-0.263	-0.165	-0.171
ΔPg at bus 21 (pu)	-0.468	0.000	0.000	-0.116
ΔPg at bus 22 (pu)	-0.001	-0.016	0.000	0
ΔPg at bus 23 (pu)	-0.404	-0.354	-0.632	0
ΔP_L at bus 1 (pu)	0.0563	-	-	-
ΔP_L at bus 2 (pu)	0.0144	-	-	-
ΔP_L at bus 3 (pu)	0.0990	-	-	-
ΔP_L at bus 4 (pu)	0.0302	-	-	-
ΔP_L at bus 5 (pu)	0.0217	-	-	-
ΔP_L at bus 6 (pu)	0.0239	-	-	-
ΔP_L at bus 7 (pu)	0.0413	-	-	-
ΔP_L at bus 8 (pu)	0.0743	-	-	-
ΔP_L at bus 9 (pu)	0.0096	-	-	-
ΔP_L at bus 10 (pu)	0.0546	-	-	-
ΔP_L at bus 13 (pu)	0.0536	-	-	-
ΔP_L at bus 14 (pu)	0.1312	-	-	-
ΔP_L at bus 15 (pu)	0.0229	-	-	-
ΔP_L at bus 16 (pu)	0.0422	-	-	-
ΔP_L at bus 18 (pu)	0.0349	-	-	-
ΔP_L at bus 19 (pu)	0.0145	-	-	-
ΔP_L at bus 20 (pu)	0.0351	-	-	-
Tap changer setting at 3-24	0.928	1.020	0.963	1.056
Tap changer setting at 9-11	1.009	1.082	0.955	0.965
Tap changer setting at 9-12	0.927	1.066	0.973	1.063
Tap changer setting at 10-11	0.971	0.909	0.905	0.934
Tap changer setting at 10-12	0.921	0.901	0.982	1.035
Capacitor #1 (pu)	0.710	0.992	0.876	0.876
Capacitor #2 (pu)	0.431	0.713	0.528	0.758
Phase shifter setting at 10-11 (degree)	-10.39	-11.30	-7.70	-8.1

congestion management due to voltage instability and thermal overload and on decreasing the cost of congestion relief. Furthermore the results depict how the different static load models can affect the cost and the margin of stability and also show the different kinds of loads can change the suitable buses for reactive power compensation. So if the loads in the system do not model correctly, the evaluated cost for congestion management wouldn't be true and accurate. Here we have shown by using more complete model of voltage stability phenomenon, not only the investigation of stability condition would be more real, but also the cost of supplying stability margin after contingencies will decrease, by means of dividing the solutions in two preventive and corrective control actions. Briefly the results show the proposed method is reasonable and practical.

Moreover from our results it can be concluded that the RPF indices can provide a complete picture of system critical areas, and also the most adequate actions to improve system security from a voltage stability perspective.

Appendix A

Reactive Power Pricing

a) Conventional method for generators:

$$\text{Cost }(P)= aP^2 + bP + c \qquad (A.1)$$

$$\text{Cost }(Q)= dQ^2 \quad (d \approx 0.05*b) \qquad (A.2)$$

b) Static compensation equipment

The production cost of any reactive power compensation equipment must include the capital investment return, which is expressed through a depreciation rate depending on its lifetime. For example, a static compensator with an initial cost of $ 11,600.00/MVAr, life time of 30 years and average use of 3/4, has a cost function as

$$\text{Cost }(Q_{sh}) = Q_{sh} *11600/(30*365*24*3/4)$$
$$= Q_{sh}*0.0589 \ \$/\text{MVAr} \qquad (A.3)$$

where Q_{sh} is the reactive power generated by the equipment. The impact of the capacitor capital investment in the reactive power cost is represented in [38].

Appendix B

Table B.1 Demand Data

Node	P_{Di}^{A} (MW)	P_{Di}^{min} (MW)	P_{Di}^{max} (MW)	r_{Di}^{up} ($/MWh)	r_{Di}^{down} ($/MWh)
1	108	75.60	142.56	20.0	22.0
2	97	67.84	128.04	20.0	22.0
3	180	126.00	237.60	20.0	22.0
4	74	51.81	97.68	21.0	23.0
5	71	49.71	93.72	21.0	23.0
6	136	95.22	179.52	21.0	23.0
7	125	87.51	165.00	21.0	23.0
8	171	119.70	225.72	22.0	24.0
9	175	122.52	231.00	20.0	23.0
10	195	136.50	257.40	21.0	23.0
13	265	185.52	349.80	20.0	22.0
14	194	135.81	256.08	20.0	22.0
15	317	221.91	461.64	19.0	21.0
16	100	70.02	132.00	19.0	21.0
18	333	233.10	439.56	19.0	21.0
19	181	126.72	238.92	19.0	22.0
20	128	89.61	168.96	19.0	21.0

Table B.2 Generators Data

Generator	P_{Gj}^{A} (MW)	P_{Gj}^{min} (MW)	P_{Gj}^{max} (MW)	r_{Gj}^{up} ($/MWh)	r_{Gj}^{down} ($/MWh)
1,2	0.0	15.80	20.0	-	-
3,4	76.0	15.20	76.0	16.0	15.0
5,6	0.0	15.80	20.0	-	-
7,8	76.0	15.20	76.0	16.0	15.0
9-11	50.0	25.00	100.0	22.0	21.0
12,13	118.2	68.95	197.0	22.0	21.0
14	89.6	68.95	197.0	20.0	19.0
15-19	0.0	2.40	12.0	-	-
20,21	155.0	54.25	155.0	12.0	11.0
22,23	400.0	100.00	400.0	7.0	5.0
24-29	50.0	50.00	50.0	100.0	100.0
30,31	155.0	54.25	155.0	12.0	11.0
32	350.0	140.00	350.0	12.5	11.5

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