

An Integrated Competitive-Approach for the Remuneration of VAR Producers in an Open-Access Environment

E. E. El-Araby *

Dept. of Electrical Engineering, College of Engineering
Qassim University, Saudi Arabia
elaraby@qec.edu.sa

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Abstract. This paper proposes a comprehensive competitive-based scheme for procuring VAR ancillary services from the dynamic sources in an open-access environment. To make an incentive for the market participants, the proposed pricing mechanism includes VAR capacity as well as VAR utilization during system operation. In order to accommodate real power system circumstances and evaluate realistically expected total VAR capacity and utilization payment during the contracted period, multiple load levels and the associated critical contingencies for each load level with their occurrence probabilities are addressed. The problem is stated as a large-scale minimization problem so that the financial and technical issues, emphasizing voltage security issue, are regarded explicitly in a new unified single formulation. The proposed formulation stresses the fairly payment in terms of the VAR capacity and VAR utilization for the worthy VAR providers that are critical for keeping system security under multiple transition states. The method has been tested on IEEE-57 bus system to examine its capability.

Keywords: deregulation, VAR market, ancillary service pricing, voltage security, PSO.

* On a temporarily leave from Port-Said University, Egypt

1. Introduction

Since the introduction of the electricity markets, there has been an intensive rise in the number of the new players that looking for a new business opportunity in this new environment. The swift increase of the new market participants has lead to a significantly rapid growth in the unpredictable interchange transactions among the utilities in manner that the transmission system is increasingly being stressed. Under these stressed conditions, a power system tends to operate closer to its physical and operation limits. In these circumstances, one of the main concerns of transmission operator “TO” is the violation of the security criterion in terms line flow limits, bus voltage limits and voltage stability margin under normal and credible contingencies. TO has the full responsibility for providing necessary ancillary services that are essential for the maintenance of the system security. Adequate provision of VAR ancillary services from the dynamic sources is critical and quite effective to enable power system to operate within an acceptable degree of reliability and security as specified in the FERC Order no. 888 [1]. The procurement of VAR services is especially challenging for TO in the aspects related to pricing mechanism and several technical issues during system operation. TO should employ a pricing mechanism that enables it to procure VAR services in a minimum payment, with insignificant economical impact on market players. Meanwhile, TO should also recognize the critical VAR providers and fairly remunerate them according to their relative worth for the system security. The technical issues that should be taken into consideration in the procurement of VAR services include the following:

- Possible power system transition states with their associated occurrence probabilities.
- Adequate VAR capacity that should be available for each state to ensure system security.
- Minimization of the VAR utilization during system operation to guarantee low economical effect of this service.

In the existing markets, it has been noted that most of transmission operators address VAR procurement challenges through long-term planning in two pricing approaches. The first approach is cost-based payment such as New York and PJM markets and the second one is market-based pricing such as UK market. The acquiring of VAR support services in these markets mainly relies on the heuristics and TO’ judgments and the above technical issues have not considered clearly in their VAR services management. Consequently, adequate security level, fairly remuneration of VAR providers and lowest payment of VAR services can't be guaranteed in these pricing schemes.

Recently, several research studies have been presented to tackle the deficiencies of the existing pricing mechanisms. References [2,3] have presented a competitive VAR market scheme for procuring VAR from generators and synchronous condensers. The succeeded candidates in this market are supposed to

get a long term contracts with TO to provide VAR services whenever called upon. Reference [4] has also introduced a market-based solution for managing VAR services by integrating VAR procurement with day-ahead energy market. The common drawbacks of [2-4] are the absence of the inclusion of expected VAR utilization payment and treatment of voltage security under normal and anticipated contingency states. Reference [5] has developed a reactive OPF used for simulation of VAR market in the UK electricity market. The VAR utilization payment and contingency states have been considered in this proposal. However, the voltage security and occurrence possibilities of contingencies are still tackling problems to be treated in this work. Reference [6] directly treats voltage security issue. Although the work is pioneering, it is not suited for the existing markets since it is based on day-ahead market, which might eventually suffer from market power problem. Reference [7] proposes a two-level frame work in a different two time horizons for the VAR ancillary service considering voltage security issue. In spite of the significant contribution of this work, the inclusion of expected VAR utilization payment under the multiple load levels with their associated critical contingencies is not addressed. Even though the previous research studies have developed worthy VAR pricing models, it is noted that a pricing proposal that considers the above financial and technical issues in unified single problem has not been yet developed, which is the concern of this paper.

The present paper is an extension of the author's proposal for the provision of the VAR service from dynamic VAR sources in a competitive market-based environment [8]. The formulation has been modified to include VAR utilization payment and possible power system transition states "multiple base cases and contingencies" with their associated occurrence probabilities. This treatment permits to accommodate real power system circumstances and consequently evaluate realistically expected total VAR capacity and utilization payment during the contracted period. The problem is stated as a minimization problem so that financial and technical issues mentioned above, emphasizing voltage security issue, are regarded explicitly in a unified single formulation. The objective function, which is the sum of expected VAR capacity payment, VAR utilization payment and operating costs during system operation, is assessed probabilistically under possible power system transition states. The proposed method is suited for the existing UK VAR market, where it can be employed for the simulation and analysis of such kind of VAR market arrangements.

2. Basic Terms of The Proposed Approach

2.1 Important Assumptions and Considerations

In this sub-section, for the sake of clarity, we identify first the key assumptions and considerations that underlie the proposed VAR market structure. The significant assumptions and considerations that have been made and used throughout this study are as follows:

I. The VAR providers that are entitled to enter this market are only generators and synchronous condensers as the case of the current practice of VAR ancillary service. Other VAR facilities will be freely used by the TO since these devices are usually under the operator's direct control and their costs are generally recovered through an access charge [1-5].

II. In this market the generators are obliged "with no payment" to provide their reactive power in proportion to their active power output. This assumption is made based on the VAR payment structures in many existing markets. The practice of these markets mandates generators to supply minimum amount of VAR with no payment as long as they have been contracted to provide VAR as an ancillary service. This obligation of VAR is usually within a specified range of power factor. According to a NERC planning standard guideline [1], reactive capability within 0.9 lagging and 0.95 leading should be available.

III. The market operates on long-term contracts "six months for example" as this trend is adopted and expected to continue in almost all of the existing electricity markets and is highly recommended in order to avoid the risk of potential market power exercise that could be associated with the limited number of regional VAR providers [2,3,5].

2.2 System Transition States

The multi-transition states that have been introduced in author previous work for the conventional VAR planning problem [9] are exploited in this work. The possible power system transitions states that considered in each investigated load level is simplified as shown in Fig.(1). We assume that, for each load level, the power system is operating at the base case A, and a contingency k will happen with probability α . When it happens, the proceeding state is assumed to be state B, which will result in either voltage collapse with probability β or corrective state C with $1-\beta$. In the corrective state, controls are carried out to meet all operational constraints using all available VAR control devices including the VAR procured from the VAR providers in the proposed VAR market. The main VAR providers of the proposed market are generators and synchronous condensers. One of the main features of these dynamic VAR sources lies in their fast control ability to react quickly against disturbances. Therefore, when focusing on the generators and synchronous condensers, the transitions of power system states of Fig.(1) may be simplified. Namely, as soon as a contingency occurs, the system state directly changes from A to C very quickly on condition that the other emergency controls also respond fast enough. In other words, it is assumed that the control coordination is perfect which contribute to prevent the occurrence of voltage collapse. According to this assumption, the probability of the contingency that proceeds the system directly to voltage collapse is assumed to be zero, i.e. $\beta=0$, and as a consequence the state B is neglected to simplify the problem.

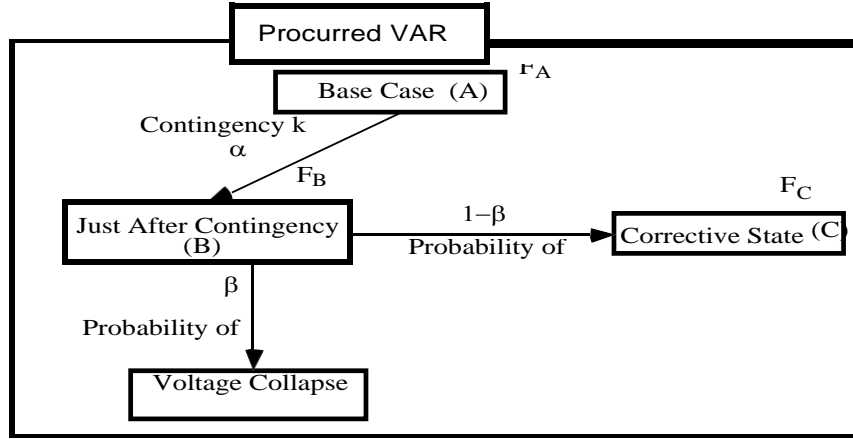


Fig. (1). System Transition States

2.3 VAR Market Objective

In this section, the basic concept of the proposed VAR procurement method is presented. Fig.(2) is assumed to illustrate and clarify the intrinsic idea behind this work. First, we suppose that TO invites VAR providers to participate in its VAR market, where the main providers are generators and synchronous condensers. The structure of this market composed of VAR capacity and VAR utilization during system operation. Then, the main target of TO is to get long term contracts “six month for example” with most beneficial VAR providers. The most beneficial providers are those that simultaneously ensure system security during expected operating states and minimize expected total TO VAR service payment. Achieving this target requires TO to specify a set of expected operating conditions with their possibilities during the contracted period. Based on the power system transition states discussed above, a set of possible operating conditions that TO may employ for this market is assumed as given in Fig.(2). It is assumed that, during contracted period, there are a number of load levels “ $L^{(1)}, L^{(2)}, \dots, L^{(T)}$ ” that TO considers significant for the analysis and simulation in this market. The corresponding time durations of these load levels are “ $D^{(1)}, D^{(2)}, \dots, D^{(T)}$ ”, while the associated base cases are “ $A^{(1)}, A^{(2)}, \dots, A^{(T)}$ ” as indicated in Fig.(2). It is also supposed that, for each load level, there are a number of contingencies N the system may be exposed for. At the load level $L^{(i)}$, when a contingency k occurs with probability $\alpha^{(k,i)}$, the system will proceed to the corrective state $C^{(i)}$. Therefore, the probability that the system will be in base case operating state at load level $L^{(i)}$ is $(1 - \sum \alpha^{(k,i)})$. According to this assumption, for load level $L^{(i)}$, the number of hours that will be spent under the outage of contingency k is $D^{(i)} \alpha^{(k,i)}$, while the number of hours that will be spent in base case is $D^{(i)} (1 - \sum \alpha^{(k,i)})$. The problem now is how to procure a minimum VAR

capacity that accommodates all of these operating states and maintain a certain degree of security for each individual state. Another problem is how to ideally utilize this VAR capacity during operation of each expected state and consequently minimize whole VAR service payment. For this purpose, the objective function is adopted to simultaneously minimize VAR capacity payment, expected VAR utilization payment and operating costs under all transition states as described by the following equation.

$$F_{Total} = F_{Cap} + \sum_{t=1}^T F^{(t)} \quad (1)$$

where

$$\begin{aligned} F^{(t)} &= D^{(t)} (F_A^{(t)} + F_C^{(t)}), \\ F_A^{(t)} &= (1 - \sum_{k=1}^N \alpha^{(k,t)}) (F_{UB}^{(t)} + F_{Opt}^{(t)}) \\ F_C^{(t)} &= \sum_{k=1}^N \alpha^{(k,t)} (F_{UB}^{(k,t)} + F_{Cc}^{(k,t)}) \end{aligned}$$

Where F_{Total} is the total objective function, F_{Cap} is the VAR capacity payment; $F^{(t)}$ is expected operating cost of the load level $L^{(t)}$; $F_A^{(t)}$ and $F_C^{(t)}$ are the expected operating costs of the base case and corrective states for the load level $L^{(t)}$; $F_{UB}^{(t)}$ and $F_{Opt}^{(t)}$ are the base case VAR utilization payment and power loss cost for load level $L^{(t)}$; $F_{UB}^{(k,t)}$ and $F_{Cc}^{(k,t)}$ are the VAR utilization payment and corrective control costs for load level $L^{(t)}$ and contingency k.

It should be mentioned that the probability of contingency happening can be calculated based on different methods. The use of historical data and statistical analysis are more common methods. For instant probability $\alpha^{(t,k)}$ can be computed using the product of frequency and duration of contingency k in a year for load level t divided by 8760. In this paper, without loss of generality, hypothetical values are used for contingency probabilities [10-11].

A detailed description of each individual objective function and its associated constraints that have been employed to ensure system security for all the above operating states will be explained hereafter.

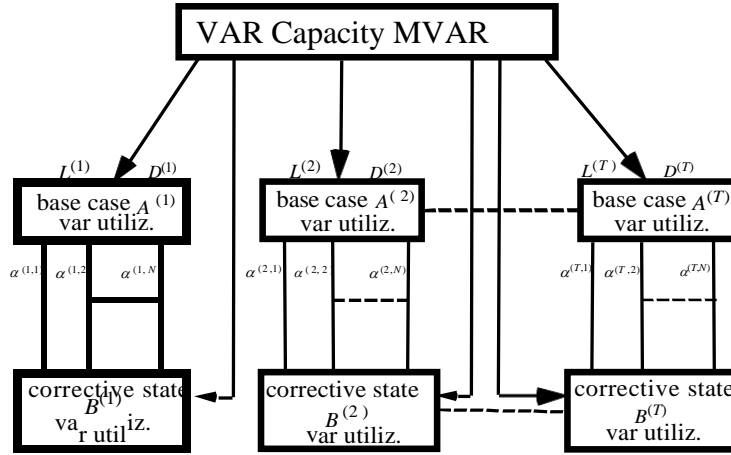


Fig. (2). Basic concept of the proposed VAR market

2.4 Generator VAR Output and its Compensation

The VAR market scheme presented here considers only the generators and synchronous condensers and depends mainly on the generator capability curve shown in Fig. (3). In this paper we assume that the generators are obligated to provide a certain amount of reactive power without any payment or compensation from the TO. This VAR amount is expressed as Q_{md1} in the lagging power factor region and Q_{md2} in the leading power factor region as shown in Fig.(3). In brief we assume that each generator will provide its VAR service as described in following regions:

Region I (Q_{md2} to Q_{md1}): The reactive power produced in this region is obligatory with no payment.

Region II (Q_{md1} to Q_1 & Q_{md2} to Q_2): This region represents the extra reactive VAR provided by generator beyond its obligatory without rescheduling its real power output. A generator in this region is expecting a payment from the TO for its service.

Region III (Q_1 to Q_1^* & Q_2 to Q_2^*): In this region the generator will reduce its real power schedule (P_{sch}) and consequently its lost revenue will be recovered by the TO. This payment is known as opportunity cost payment. The adjustment of the real power schedule corresponding to VAR output can be computed based on the slope of line segment Q_1 Q_1^* or Q_2 Q_2^* since the data of Fig.(3) are assumed to be submitted to TO in the proposed scheme.

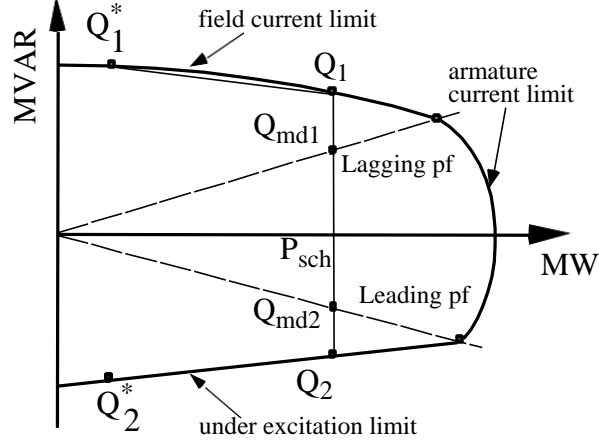


Fig. (3). Generator Capability Curve

Based on the classification of the above regions, a bidding scheme that allows the TO to procure VAR service from generators and synchronous condensers in competitive manner is introduced. This market consists of VAR capacity and VAR utilization during the expected transition states. Therefore, the generators and synchronous condensers will provide their VAR capabilities in MVAR and their associated offer prices in \$/MVAR for the recovery of the VAR capacity. Also they are required to submit their VAR utilization offer prices in \$/MVARh in order to recover the VAR utilization during system operation. The bidding method mainly relies on the generator VAR payment function depicted in Fig.(4).

The mathematical expression of the VAR capacity payment F_{Cap} is given by equation (A1) in Appendix A. The VAR capacity pattern acquired based on (A1) will be utilized in the normal state and emergency situations, where each successful provider will make its contracted VAR capacity available for the TO to mitigate constraint violations and to guarantee its desired security level during operation.

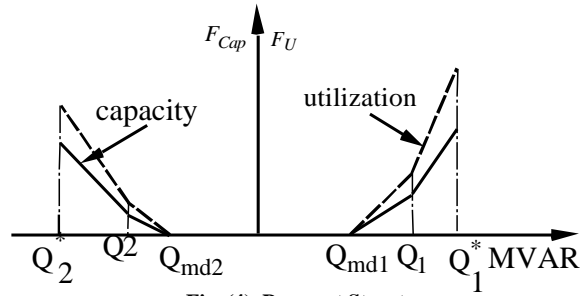


Fig. (4). Payment Structure

For the recovery of the VAR utilization, the bidding criterion is identical to the VAR capacity payment. Namely, the generators will provide their offer prices in \$/MVARh for each region discussed above and the utilization payment will be determined according to the VAR utilized in the system operation by employing the VAR utilization payment equation given in the Appendix B:

3. Transition States Consideration in The Problem Formulation

This section is devoted to develop the main contribution of this study, where the mathematical formulation that considers VAR capacity payment, utilization payment and operating costs under the previous transition states in a unified single problem is introduced. The generators and synchronous condensers are merely the main providers of the VAR service in the proposed formulation. The mathematical formulation for each transition state introduced for the conventional VAR planning problem [9, 10] has been modified to meet the economical and technical issues mentioned in section 1.

3.1 Base Case Sub-problems

The base case sub-problems evaluate the operation cost of the normal states under specific number of load levels stipulated by TO. As we have mentioned before, for each load level, the power system is supposed to operate for a certain period of time. Therefore, choosing a proper objective function to be minimized in the normal operation throughout duration time of each load level can effectively satisfy adequate payment of VAR service. In this paper, the cost of the power loss and VAR utilization payment are selected as the main objective function in each base case sub-problem. To maintain voltage stability margin requirement, two sets of constraints have been included in the formulation for each base case. The first set represents the equality and inequality constraints at the nominal load operating point and the second set represents the equality and inequality constraints at the point of collapse. According to this assumption, the base case sub-problem of the load level $L^{(i)}$ is formulated as:

$$\text{Minimize} \quad F_A^{(t)} = (1 - \sum_{k=1}^N \alpha^{(k,t)}) (F_{UA}^{(t)}(Q_b^{(0)}) + F_{Opt}^{(t)}(x_b^{(0)}, p_b^{(0)}, Q_b^{(0)})) \quad (2)$$

subject to

$$\left. \begin{aligned} y_b - (r_2 + r_4) dp_{sch} - s_b^{(0)} - f(x_b^{(0)}, p_b^{(0)}, Q_b^{(0)}) &= 0 \\ 0 \leq s_b^{(0)} \leq s_{\max}^{(0)}, \quad x_{\min} \leq x_b^{(0)} \leq x_{\max} \\ p_{\min} \leq p_b \leq p_{\max}, \quad Q_{\min} \leq Q_b^{(0)} \leq Q_{\max} \end{aligned} \right\} \quad (3)$$

$$\left. \begin{aligned}
& y_b + (\lambda_c^{(0)} - 1) y_d (r_{2+} r_4) dp_{sch} - s_c^{(0)} - f(x_c^{(0)}, p_c^{(0)}, Q_c^{(0)}) = 0 \\
& w(x_c^{(0)}, p_c^{(0)}, Q_c^{(0)}, s_c^{(0)}, \lambda_c^{(0)}) f_x(x_c^{(0)}, p_c^{(0)}, Q_c^{(0)}, s_c^{(0)}, \lambda_c^{(0)}) = 0 \\
& \|w\| \neq 0 \\
& 0 \leq s_c^{(0)} \leq s_c^{\max}, \quad \lambda_c^{(0)} \leq \lambda_c^{\min(0)} \leq Q_c^{\max}
\end{aligned} \right\} \quad (4)$$

where

$$\begin{aligned}
Q_{\min} &= Q_{md2} + r_1 Q_{g1} + r_2 (Q_2 - Q_{md2}) + r_2 Q_{g2} \\
Q_{\max} &= Q_{md1} + r_3 Q_{g3} + r_4 (Q_1 - Q_{md1}) + r_4 Q_{g4}
\end{aligned}$$

where (3) with the subscripts b and (4) with c indicate the nominal load operating point and collapse point respectively. Constraints (3) consist of ac power flow equations, operation limits of voltage magnitude, angle, load shedding, VAR devices including generators, synchronous condensers, etc. Constraints (4) consist of conditions for voltage collapse point, which include a set of point of collapse equations, limits of control devices, load shedding and load power margin for security. $F_{opt}^{(t)}$ is power loss cost for load level $L^{(0)}$. $F_{UA}^{(t)}$ is base case VAR utilization payment for load level $L^{(0)}$. The superscript (0) refers to the base case sub-problem. x is the state variables vector “voltage magnitudes and angles”. s is load shedding vector. p is the control variables vector “VAR control devices” excluding Q . y_b is nominal load “base case”. y_d is load direction vector. Q is the generator and synchronous condensers VAR output. f is power flow equations at nominal load. w is left eigenvector “row vector”. f_x is power flow Jacobian “singular at nose point”. dp_{sch} is the change of active power schedule in region III. λ is the load parameter value.

Note that the equality constraints at the point of collapse stand for the conditions of the saddle node bifurcations, which are useful in identifying λ [12]. Another important point is that the term $(r_{2+} r_4) dp_{sch}$ in (3) and (4) will only be active when generator provides its VAR in region III. Otherwise this term will be null.

In the above formulation, in order to simplify the problem, the utilization payment $F_{UA}^{(t)}$ is expressed as a linear function of the reactive power output of each provider “ $Q_b^{(0)}$ ”. This simplification enables us to treat each base case sub-problem in the implementation as nonlinear programming problem as we will discuss

hereafter. Consequently, based on the output of the reactive power $Q_b^{(0)}$, the var utilization and its associated payment is calculated. For instance, when the lagging var output $Q_b^{(0)}$ is between zero and Q_{md1} , the reactive power utilization Q_{u3} and Q_{u4} are equal zero and consequently $F_{UA}^{(t)}$ is equal zero. When the lagging VAR output $Q_b^{(0)}$ is between Q_{md1} and Q_1 , the VAR utilization Q_{u4} is equal zero and the reactive utilization Q_{u3} and its associated payment are computed based on the linear segment $Q_{md1} Q_1$. Finally, when the lagging VAR output $Q_b^{(0)}$ is between Q_1 and Q_1^* , $Q_{u3} = Q_1 - Q_{md1}$, while Q_{u4} and its associated payment are calculated based on the linear segment $Q_1 Q_1^*$.

3.2 Post-Contingency States Sub-problems

As indicated in Fig.(2), for each load level $L^{(i)}$, there are a number of contingencies N that proceed the system to the corrective states, where each contingency will be remained for a certain period of time. The main objective here is to employ a proper objective function that ensures a minimum VAR services payment in these states while maintaining system security. To achieve this purpose, for each contingency, the corrective control actions are assumed based on the reactive power controls and load shedding to guarantee the system security. We assume that the VAR control costs are trivial compared with the load shedding cost. The objective function is chosen to minimize simultaneously the expected total amount of the control costs and VAR utilization payment while satisfying the constraints set for the nominal load operating point and the collapse point. The formulation of this problem for the load level $L^{(i)}$ is stated as:

$$\begin{aligned} \text{Minimize } F_C^{(t)} &= \sum_{k=1}^N F_C^{(k,t)} \\ F_C^{(k,t)} &= \alpha^{(k,t)} (F_{UB}^{(k,t)}(Q_b^{(k)})) + F_{Cc}^{(k,t)}(p^{(0)}, p^{(k)}, s^{(k)}, Q^{(0)}, Q^{(k)}) \\ F_{Cc}^{(k,t)}(p^{(0)}, p^{(k,t)}, s^{(k,t)}, Q^{(0)}, Q^{(k,t)}) &= \\ &= \left\{ \sum_l \mu_{sl} |s^{(k,t)}| + \sum_i \mu_{pi} |p^{(k,t)} - p^{(0)}| + \sum_j \mu_{qj} |Q^{(k,t)} - Q^{(0)}| \right\} \end{aligned} \quad (5)$$

Subject to

$$\begin{aligned} G_b^{(k,t)}(x_b^{(k,t)}, p_b^{(k,t)}, s_b^{(k,t)}, Q_b^{(k,t)}, \lambda_b^{(k,t)}) &\leq 0 \\ G_c^{(k,t)}(x_c^{(k,t)}, p_c^{(k,t)}, s_c^{(k,t)}, Q_c^{(k,t)}, \lambda_c^{(k,t)}) &\leq 0 \end{aligned} \quad k=1:N \quad (6)$$

where $G_b^{(k,t)}$ and $G_c^{(k,t)}$ are similar to the constraints (3) and (4) respectively except that the superscript k refers to post- contingency state and the load shedding s is included. μ_{sl} , μ_{pi} and μ_{qj} are unit control cost coefficients of s , p and Q respectively. $F_{UB}^{(k,t)}$ and $F_{Cc}^{(k,t)}$ are VAR utilization payment and corrective control cost for the load level $L^{(t)}$ and contingency k . Similar to the base case sub-problems, based on the output of the reactive power $Q_b^{(k,t)}$, the VAR utilization Q_{u1} , Q_{u2} , Q_{u3} and Q_{u4} and its associated payment $F_{UB}^{(k,t)}$ will be determined.

3.3 Overall Problem Formulation

To guarantee the economic efficiency of the VAR service, we simultaneously minimize the total payment of procured VAR and operating costs in normal and contingency states as follows:

$$\text{Minimize } F_{Total} = F_{Cap} + \sum_{t=1}^T D^{(t)} (F_A^{(t)} + F_C^{(t)}) \quad (7)$$

Subject to: Generator constraints (A2- A4)

Base case constraints (3) and (4)

Post-contingency states constraints (6)

4. Solution Algorithm

The overall problem (7) is deemed as a large-scale mixed integer nonlinear optimization problem. The classical optimization methods do not work efficiently and often encounter a great difficulty in handling such kind of hard optimization problems. The heuristic techniques are a good alternative in such situation as they are more often capable of attaining satisfactory solutions in a reasonable amount of time to the challenging problems as the problem we are addressing. Accordingly, an optimization technique based on a particle swarm optimization [13] and successive linear programming (PSO/SLP) for finding a global optimal solution of (7) is presented in this section. The computational procedures of the proposed method are summarized in Fig.(5). The algorithm starts from a random initial swarm, where its particles are indicated in Fig.(5) by Prc.1, Prc.2,..., Prc.1. Each particle in the swarm represents a candidate solution, i.e., a pattern of generators VAR capacity. For instant, assume particle 1 (Prc.1) represents a candidate pattern of generators VAR capacity, where its payment F_{Cap} can directly computed using equation (A1). This candidate pattern is used as a common candidate for each transition state in the load levels “L(1), L(2), ..., L(T)” to minimize operating costs and VAR utilization payment during normal operation and emergency states. For each load level, the

SLP is used to solve individually the base case optimization sub-problem (2-4) and its associated post-contingency states sub-problems (5-6). The expected operating costs “ $F(1), F(2), \dots, F(T)$ ” of the load levels “ $L(1), L(2), \dots, L(T)$ ” are computed in these optimization problems. According to the optimization results, the fitness of prc.1 is evaluated in terms of F_{Cap} , $F(1), F(2), \dots$ and $F(T)$. The same computational procedures will be repeated for each particle in the swarm. Consequently, the best previous position for each particle and best particle among all the particles are stored in a solution set. Then, the new velocity and position for each particle are updated based on current velocity, current position, producing next iteration. These procedures are repeated till a termination criterion is satisfied.

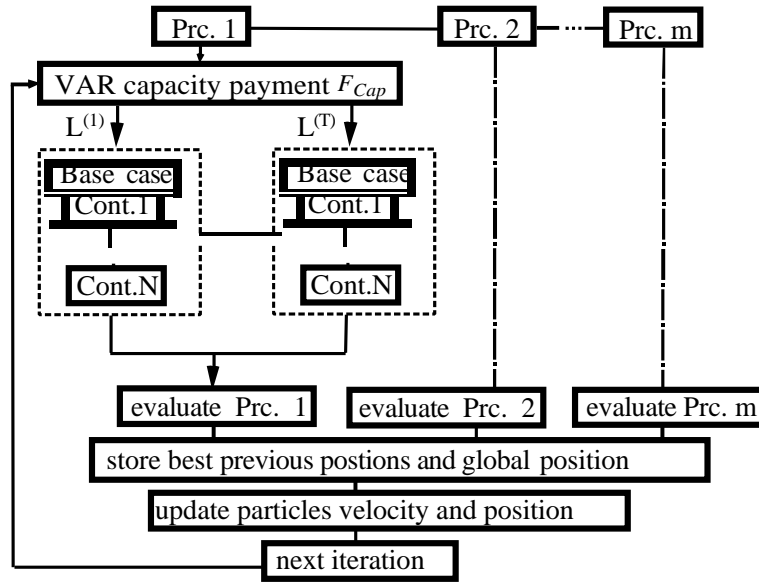


Fig. (5). A hybrid PSO/SLP Solution Method

5. Simulation Results

The proposed method of VAR market scheme was tested on modified IEEE 57 bus system shown in Fig.(6). The analysis were executed for three load levels ($NL=3$) at 130%, 140 % and 150 % of the original load. The corresponding time durations (T) of the three load levels are set 70%, 20% and 10% respectively. Two severe contingencies have been adopted for each load level for the examination. The severe contingencies of 130% load level were the outages of lines (25-30) and (46-47) with probabilities 0.03 and 0.025 respectively. The outages of lines (25-30) and (46-47) with probabilities 0.02 and 0.015 are assumed for the load level 140%. The

associated contingencies and probabilities for the third load level 150% are the outages of lines (25-30) and (46-47) with probabilities 0.01 and 0.005 respectively. The objective of TO in this simulation is to get a long term contract with the promising VAR providers in a minimum payment while keeping the load margin ≥ 0.25 and bus voltage magnitudes within 0.9-1.1 pu. The minimum payment means that a simultaneous minimization of the expected VAR capacity and VAR utilization payment under the previous transition states. The period of long term contract is assumed 180 days. According to the contracted period and the data given above the time duration of each transition state is indicated in table (1).

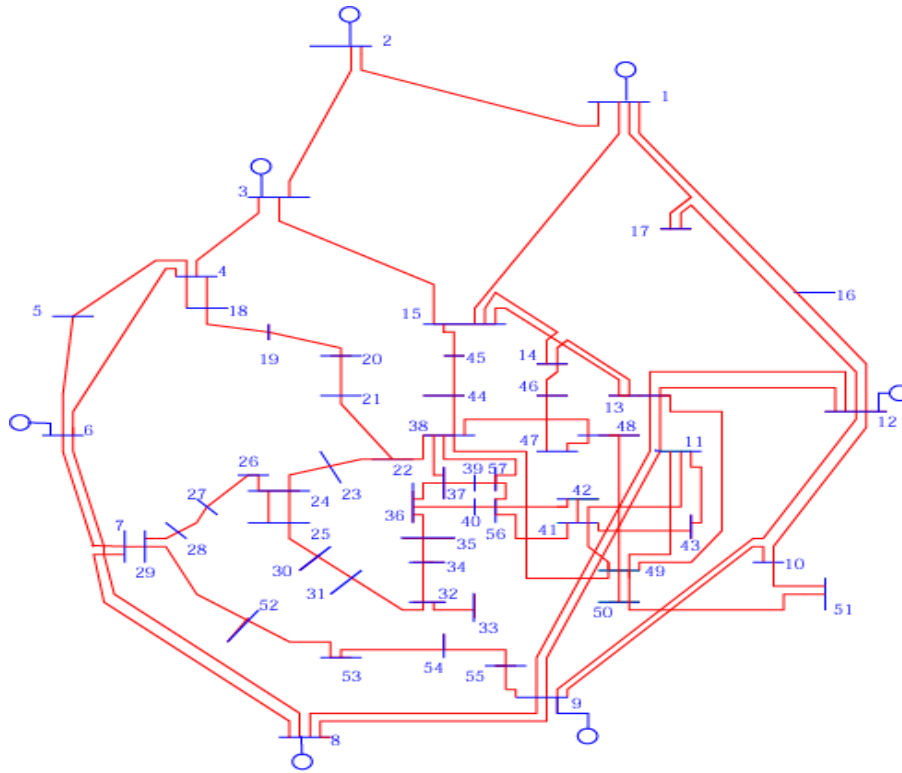


Fig. (6). IEEE-57 bus system.

Table (1). Time durations of the transition states "hours".

Load Level	1.3	1.4	1.5
Base case	2786.4	712.8	367.2
Cont 1	129.6	86.4	43.2
Cont 2	108.0	64.8	21.6

Table (2) shows the offered prices in \$/MVAR and \$/MVARh for the recovery of the VAR capacity as well as VAR utilization during system operation respectively. The VAR capabilities of each region associated with each load level are also indicated in the table. The data given in table (1) is provided for only the lagging region which is vital for the voltage stability problem. Note that the providers 1, 3 and 5 are synchronous condensers and therefore their VAR mandatory obligations and opportunity offer prices are set zero as shown in Table (2).

Table (2). Generators and synchronous condensers offers.

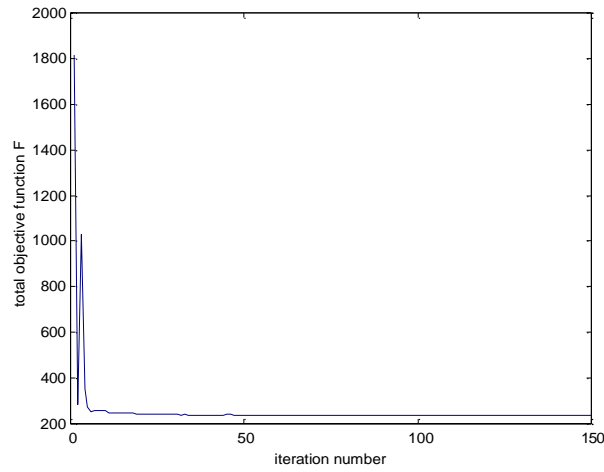
		Generator	1	2	3	4	5	6
Capacity prices		μ_3, μ_4	24,0,0	21, 37.5	18,0,0	25.5,34.5	17.4,0,0	23.4,42
Utilization prices		H_3, H_4	0.016, 0.0	0.014, 0.05	0.012, 0.0	0.017, 0.046	0.012, 0.0	0.016, 0.056
Load level	1.3	Q_{md1}, Q_1, Q_1^*	0.0, 0.5, 0.5	0.17, 0.79, 0.97	0.0, 0.25, 0.25	1.92, 2.77, 3.25	0.0, 0.09, 0.09	1.32, 2.07, 2.52
			0.0, 0.5, 0.5	0.18, 0.77, 0.97	0.0, 0.25, 0.25	2.07, 2.63, 3.25	0.0, 0.09, 0.09	1.42, 2.00, 2.52
			0.0, 0.5, 0.5	0.20, 0.75, 0.97	0.0, 0.25, 0.25	2.22, 2.50, 3.25	0.0, 0.09, 0.09	1.53, 1.94, 2.52
	1.4	Q_{md1}, Q_1, Q_1^*	0.0, 0.5, 0.5	0.17, 0.79, 0.97	0.0, 0.25, 0.25	1.92, 2.77, 3.25	0.0, 0.09, 0.09	1.32, 2.07, 2.52
			0.0, 0.5, 0.5	0.18, 0.77, 0.97	0.0, 0.25, 0.25	2.07, 2.63, 3.25	0.0, 0.09, 0.09	1.42, 2.00, 2.52
			0.0, 0.5, 0.5	0.20, 0.75, 0.97	0.0, 0.25, 0.25	2.22, 2.50, 3.25	0.0, 0.09, 0.09	1.53, 1.94, 2.52

Based on the data submitted in table (2), the solution algorithm given in section 4 is executed. The parameters of PSO used in the simulation are: $\omega_{\min}=0.4$,

$\omega_{\max}=0.9$, $c_1=c_2=2$, $v_{id\min}=-2$ $v_{id\max}=2$, swarm sizes 20. The optimal VAR procured from the VAR providers 1 to 6 are 0.193, 0.789, 0.25, 2.51, 0.09 and 1.94 pu respectively. The associated total cost is 233.75. The convergence characteristic for this examination is given in Fig.(7).

Table (3). VAR utilization payments and operating costs .

	Load Level	1.3	1.4	1.5
VAR Utilization Payment	Base case	49.6546	15.9696	9.6945
	Cont 1	2.3000	2.0177	1.1035
	Cont 2	1.8779	1.5138	0.5643
Operating Costs	Base case	66.1655	20.0624	12.2990
	Cont 1	0.0000	0.0000	0.0000
	Cont 2	0.0000	0.0000	0.0000

**Fig. (7).** Convergence Characteristic of PSO/SLP

The procured VAR are used to maintain the desired minimum voltage magnitude "0.9" and load margin value "0.25" during operation for all the expected transition states "base cases and contingency states". The total cost stands for the VAR capacity payment, VAR utilization payment and the operating costs "power losses and control costs". The total capacity payment is 50.52, which represents the sum of capacity payments associated with above load levels and their expected contingencies. The capacity payment for the load levels 1.3, 1.4 and 1.5 are 37.08, 9.36 and 4.08 respectively. Note that, the more the load level is, the lesser its capacity payment. That is occurred as a results of the increasing of real power schedules for the generators and consequently their VAR mandatory obligations are increased to ensure the transfer of the real power. According to the expected time duration given in table (1), the procured VARs are exploited during system operation for all the transition states. The VAR utilization payments and operating costs corresponding to each state are shown in table (3). Observe that, the load level

1.3 has the highest base case utilization payment since its time duration is much higher than the load levels 1.4 and 1.5. Note also that, since the time durations for the contingency cases are much lower than the base cases, the utilization payments are too low compared to the base cases for all load levels. The operating costs are mainly the base case costs which stand for the power losses costs associated with each load level. The control costs are almost zero since their unit costs are set too low in the simulation.

6. Conclusions

An integrated market-based scheme which considers both of VAR capacity and VAR utilization payments for pricing the dynamic VAR sources is introduced. A new unified single formulation that incorporate financial issue in terms of VAR service payment and technical issues considering system transition states, emphasizing voltage security issue, is presented.

The objective function, which is the sum of expected VAR capacity payment, VAR utilization payment and operating costs during system operation, is assessed probabilistically under possible power system transition states "multiple base cases and contingencies". The method has been tested on IEEE-57 bus system, where the results demonstrate its rigorous applicability. The proposed method is suited for the existing UK VAR market, where it can be employed for the simulation and analysis of such kind of VAR market arrangements.

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Appendix A: VAR Capacity Payment Formulation

The mathematical expression of the VAR capacity payment is given by the following equation:

$$F_{Cap} = (-\mu_1 Q_{g1})r_1 - \mu_1(Q_2 - Q_{md2})r_2 - (\mu_2 Q_{g2})r_2 + (\mu_3 Q_{g3})r_3 + \mu_3(Q_1 - Q_{md1})r_4 + (\mu_4 Q_{g4})r_4 \quad (A1)$$

With the constraints A2 and A3 representing leading and lagging regions respectively.

$$r_1(Q_2 - Q_{md2}) \leq Q_{g1} \leq 0, \quad r_2(Q_2^* - Q_2) \leq Q_{g2} \leq 0 \quad (A2)$$

$$0 \leq Q_{g3} \leq (Q_1 - Q_{md1})r_3, \quad 0 \leq Q_{g4} \leq (Q_1^* - Q_1)r_4 \quad (A3)$$

$$r_1 + r_2 + r_3 + r_4 \leq 1 \quad (A4)$$

where the coefficients (μ_1, μ_3) and (μ_2, μ_4) are the offer prices in \$/MVAR that the generators provide for regions II and III respectively; (Q_{g1}, Q_{g3}) and (Q_{g2}, Q_{g4}) are variables to be determined corresponding to provided VAR amounts in regions II and III respectively; Q_1, Q_1^*, Q_2 and Q_2^* are parameters to be offered by the generators; r_1, r_2, r_3 and r_4 are binary variables. According to (A4) only one of these binary variables can be selected. This constraint ensures that VAR output of generators will be in only one of the defined three regions.

Appendix B: Formulation of VAR Utilization Payment

The VAR utilization payment is represented mathematically as follows:

$$F_U = (-\mu_{u1}Q_{u1})r_1 - \mu_{u1}(Q_{u1})r_2 - (\mu_{u2}Q_{u2})r_2 + (\mu_{u3}Q_{u3})r_3 + \mu_{u3}(Q_{u3})r_4 + (\mu_{u4}Q_{u4})r_4 \quad (B1)$$

With the constraints B2 and B3 representing leading and lagging regions respectively.

$$r_1Q_{g1} \leq Q_{u1} \leq 0, r_2Q_{g1} \leq Q_{u1} \leq 0, r_2Q_{g2} \leq Q_{u2} \leq 0 \quad (B2)$$

$$0 \leq Q_{u3} \leq r_3Q_{g3}, 0 \leq Q_{u3} \leq r_4Q_{g3}, 0 \leq Q_{u4} \leq r_4Q_{g4} \quad (B3)$$

where the coefficients (μ_{u1}, μ_{u3}) and (μ_{u2}, μ_{u4}) are the offer prices in \$/MVARh that the generators provide for regions II and III respectively; (Q_{u1}, Q_{u3}) and (Q_{u2}, Q_{u4}) are the utilized VAR amounts to be determined in regions II and III respectively. In the above equations, the constraints (B2) and (B3) guarantee the VAR utilization variables Q_{u1}, Q_{u2}, Q_{u3} and Q_{u4} to be within the committed VAR capacity Q_{g1}, Q_{g2}, Q_{g3} and Q_{g4} for each individual region respectively.

تناول تنافسي متكامل للتعويض المادي لمنتجي القدرة غير الفعالة في سوق الكهرباء المفتوح

السعيد السيد العربي*

رئيس المندوبة الكهربائية - كلية المندوبة - جامعة القصيم
elaraby@qec.edu.sa

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ملخص البحث. يقدم هذا البحث افتراحاً جديداً للحصول على خدمة القدرة غير الفعالة من المصارف الدينامكية (المولدات أو الملتفات المزامنة) المأخوذة هنا لتقديم هذه الخدمة في سوق الكهرباء الحالي. السوق التنافسية المقترحة للقدرة غير الفعالة تشمل كل من السرعة المطلوبة بالإضافة إلى السنغال للقدرة غير الفعالة أثناء التشغيل وذلك لإنجاز الملتفات للدخول في سوق تزويد القدرة غير الفعالة. حلاوة وحل للأنظمة الحلقية الملوحة حالياً من الأخذ في الاعتبار حالات التشغيل البت يمكن أن يتعرض لها النظام حيث تشمل حالات أساسية متعددة واجتمعتها بالإضافة إلى احتمالية حدوث حالات طارئة مألوفة لكل حالة أساسية. وقد وضع الماشكلة لأول مرة في صيغة موحدة تشمل جميع الحالات المذكورة وذلك للتقييم المتكامل لإدلة الهدف والبت تشمل تصغير التكلفة المتوقعة لكل من السرعة المطلوبة من خدمة القدرة غير الفعالة وكذلك سنغالها بالإضافة إلى نص غير التكلفة المتوقعة للتشغيل والتحكم. وتؤكد الصيغة المقترحة على المأسائل المألوفة وفي وقت واحد حيث تضمن السنغال المثل للقدرة غير الفعالة المتاحة للحفاظ على استقرار الجهود أثناء حالات التشغيل المتكاملة وبالتالي من الوصول إلى أقل تكلفه ممكنه لهذه الخدمة. وقد من

تطبيق الطريقة المقترحة على شبكة IEEE المكونة من 75 حامل قضبان وذلك لتوضيح كفاءتها وفاعليتها.

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