International Journal of Industrial Electronics, Control and Optimization © 2018 IECO

Vol. 1, No. 1, pp. 41-51, June (2018)

Optimal allocation and sizing of dynamic VAR support to improve short-term voltage stability considering wind farm and dynamic load model

Parnian Fakhrooeian,[a] **Mehrdad Abedi**,[b] and **Peyman Karimyan**[c]

ABSTRACT

Nowadays short-term voltage instability is a major threat for power system reliability and stability owing to the increasing proportion of renewable energy sources such as solar and wind power, induction motor loads, HVDC links and etc. The aim of this paper is to determine the optimal location and size of static VAR compensator (SVC) to counteract the short-term voltage instability. A multi-objective optimization problem (MOP) is defined to satisfy the two objective functions: 1) minimizing the whole investment cost 2) minimizing the undesirable behavior of transient voltage under multiple probable contingencies. Composite load model consisting of induction motor loads and other components is modeled accurately. Moreover, the system is considered with a high penetration of wind power. Severity and risk indices are proposed to measure the degree of transient voltage performances. Candidate buses for SVC deployment are determined based on trajectory sensitivity analysis. Genetic algorithm is employed to find optimal allocation of SVC. The effectiveness of proposed approach is verified on New England 39-bus system.

ARTICLE INFO

Keywords:
Dynamic VAR support
FACTS devices
Multi-objective optimization
Reactive power planning
Short-term voltage stability
Wind farm
Article history:
Received March. 13, 2018
Accepted Aprill. 16, 2018

I. INTRODUCTION

The issue of maintaining power system stability such as voltage stability and transient stability has been recognized as one of the most major difficulties in power system operation that has been challenging the operators and power system engineers from the past decades. Voltage Instability may reflect in the form of a continuous fall or rise of voltages and quick voltage collapse at some buses following a disturbance that may lead to cascading outages or rise the risk of catastrophic blackouts. Many major blackouts throughout the world have been originated from this phenomenon[1]. Voltage stability is a problem in power systems which are lack of having VAR support, heavily loaded or being subjected to the disturbance[2] and its possible results are tripping of transmission lines and other elements, loss of loads in an area where voltages reach to unacceptable values[3,4].

Short-term voltage stability is one of the issues of concern which is relatively neglected in comparison with long-term ones[5]. This type of stability involves fast dynamic loads such as induction motor loads (e.g. air-conditioners), the increasing proportion of distributed generation consuming reactive power without voltage control, electronically controlled loads, and introduction of HVDC converters[3]. For that reason, dynamic loads should be modeled accurately because they tend to restore their consumed power in the time scale of a second after a voltage fall as a consequence of being subjected to a contingency[6]. When a large disturbance takes place, the induction motors decelerate considerably. The induction motors stall if the electrical torque cannot overcome the mechanical load and absorb a high reactive current which leads to drop of voltage in remarkable regions of the system.

On the other side, the wind power penetration has increased significantly in recent years. With the increasing growth of wind energy resources, the wind farm capacity is growing constantly through the installation of more wind turbines; for the sake of its random and unanticipated behavior, maintaining voltage stability is the basic requirements for greater penetration of wind turbines, otherwise it can have adverse effects on power systems operation. Hence, in order to avoid voltage collapse and maintain the power system in secured operating condition, fast and dynamic reactive compensation may be essentially used following a large disturbance.

In terms of compensation planning, the flexible AC transmission system (FACTS) devices can control the voltage magnitude and phase angle by regulating reactive and active power control. Additionally, FACTS devices boost the grid efficiency and minimize losses. That being so, with adequate VAR support by static compensator (STATCOM) and static VAR compensator

---

[a] Electrical Engineering Department, Amirkabir University of Technology, Iran
[b] Electrical Engineering Department, Amirkabir University of Technology, Iran
[c] Corresponding Author: peyman.sena@gmail.com, Tel: +98 (21) 64543311, Fax: +98 (21) 66406469, Electrical Engineering Department, Amirkabir University of Technology, Iran

http://dx.doi.org/10.22111/ieco.2018.2018.24388.1024

Nomenclature

P_L	Large motor	b_j	Binary decision variable
P_S	Small motor	H	Inertia
P_T	Transformer saturation	j	Buses
P_D	Discharge lighting	$V_{j,t}$	Voltage magnitude of bus j at time t
P_C	Constant power load	N	Entire number of contingencies
K_P	Constant impedance load	c	Contingency
X	Branch reactance	P_c	Probability percentage of c
R_e	Branch resistance	C_j	Capacitive capacity of SVC at bus j
R_A	Stator resistance	T	The total transient time simulation
X_A	Stator reactance	$t_{clearance}$	Clearance time
X_m	Magnetizing reactance	u	Decision variables
R_1, R_2	Rotor resistances	$\text{Cost}_{\text{purchase}}$	SVC purchase cost
X_1, X_2	Rotor reactances	$\text{Cost}_{\text{instal}}$	SVC installation cost

(SVC) and other FACTS devices, voltage profile and voltage security will be provided, hence it prevents from unacceptable transient voltage performance and frustrates short-term voltage instability. This paper concentrates on dynamic VAR planning to mitigate short-term voltage stability problems.

In the literature, most of the approaches have focused on improving the steady-state voltage stability by finding optimal placement of FACTS devices without considering short-term voltage instability[7–9]. The following works investigate this phenomenon.

In[10], a novel approach based on trajectory sensitivity is proposed in order to determine suitable placements of SVCs and STATCOMs to improve short-term voltage stability.

In[11], the optimal allocation of STATCOM has been addressed to prevent short-term voltage instability in power systems using a multi-objective evolutionary algorithm (MOEA/D). In[12], constrained optimal power flow (SOPF) is used to improve stability performance considering short-term voltage and rotor angle criteria using SVCs. In[6], the issue of short-term voltage stability analysis has been reviewed. It investigates the impacts of using STATCOM and D-SMES (Distributed Superconducting Magnetic Energy Storage) against voltage collapse and load loss. In[1], an integrated heuristic optimization has been proposed for optimal allocation and sizing dynamic VAR sources considering multiple contingencies according to a reference short-term voltage response. In[13], a new MOP model has been utilized to place STATCOM using an improved version of MOEA/D against short-term voltage instability. In[14], Cat Swarm Optimization has been employed to determine the optimal placement of Unified Power Flow Controller (UPFC) for voltage stability improvement. In[15], the effects of SVC, STATCOM , TCSC and HVDC on voltage stability boundary has been investigated; It finds the location for them to improve short-term voltage instability problems. In[5], short-term voltage instability issue has been discussed and investigated how to counteract it using SVC testing on two systems including wind farms with induction generators. In[16], maintaining short-term voltage stability has been explored owing to the large wind power systems with a probable lack of voltage control and reactive-power; compensation is done by SVC. In[17], a mixed integer dynamic optimization (MIDO) is used to address the optimal placement of SVC which is converted into mixed integer nonlinear problem solving by B&B algorithm. In[18], the effectiveness of STATCOM to facilitate integration of a large wind farm into a weak power system has been studied. The size and location of STATCOM are assessed through VQ and PV curves obtained from simulation. In this area, the most of studies have focused on utilizing VAR support to improve short-term voltage stability without considering combination of load variation and renewable energy sources in power system.

In this paper, the effects of wind farm and a Composite Load Model, which consists of dynamic and static load model, on short-term voltage stability are explored by proposed indexes. Then, a MOP compromising two objective functions is solved using Genetic Algorithm to find optimal location and size of SVC, as a dynamic VAR supporter, to mitigate short-term voltage stability problems and minimize the total investments costs. In this paper, a new approach to interface between MATLAB and Digsilent is introduced to solve the optimization problem.

The rest of this paper is organized as follows: Section II, describes the problem and modeling. In Section III, the mathematical formulation is described. Section IV presents the proposed Genetic Algorithm and computation process. In Section V, simulation results are presented. Finally, in Section VI, the conclusions derived from this work and the future works are summarized.

II. PROBLEM DESCRIPTIONS

A. Basic of SVC

Static Var Compensator (SVC) is one of the most crucial elements of FACTS devices due to its technical and economic advantages. SVC is a static electrical system which can exchange inductive or capacitive current, hence it generates and absorbs reactive power. This dynamic VAR source must be connected in parallel to the network; SVC output changes such that specific parameters of the electrical power system (regularly, the bus voltage) will be maintained or controlled. In comparison with the classical shunt-connected compensators, SVC controls transient and steady-state voltage efficiently due to its accessibility and quick response. SVC has various kind of structures; it can be classified into Thyristor-Switched Reactor (TSR), Thyristor-Controlled Reactor (TCR) or Thyristor-switched capacitors (TSCs). Continuous control can happen by using TCR because it is larger than TSC block. As a consequence, in this paper Thyristor Controlled Reactor (TCR) with Fixed Capacitor (FC) is used.

Voltage-current characteristics of the SVC act in a way that If the SVC current becomes greater than capacitive current, SVC turns into a fixed capacitor and its VAR output decreases quadratically with the bus voltage drop[5]; this is one of the SVC drawbacks.

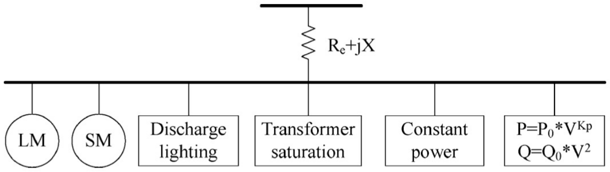


FIG. 1. Composite load model (CLOD).

TABLE I. Clod parameters perentages

P_L	P_S	P_T	P_D	P_C	K_P	X	R_e
21 %	31 %	0	6 %	31 %	2	0	0

B. Wind Turbine

The wind turbines used in this paper are Doubly Fed Induction Generators (DFIGs) that are classified in the category of variable speed turbines. Todays, DFIGs are becoming increasingly popular for the sake of their better performance than constant speed turbine during the fault. In this study, a wind farm with the capacity of 300 (MW) is connected to bus 15. For that reason, 120 DFIG turbines with the capacity of 2.5 (MW) available in Digsilent library are applied.

C. Load Modeling

The topic of load modeling and the influence of dynamic loads on voltage stability have been covered in[19–23]. As discussed above, fast recovering load components tend to restore their consumed power during a very short time frame (several seconds) following a voltage fall as a consequence of a contingency which may result in voltage instability[24]. In this way, one of the key issues to reach to an accurate simulation results is the ability of the representation of load modeling precisely.

In this paper, the composite load model (CLOD) has been deployed which is illustrated in Fig. 1. The CLOD type model is composed by large motors, small motors, constant power load, transformer saturation, discharge lighting, constant impedance load, and branch resistance and reactance. The composite load model parameters with their percentages are presented in Table I. For detailed standard composite load modeling purposes, PSS/E version 33.0 released by Siemens can be used[25].

1. Induction Motor Loads

Both large and small induction motors are modeled as double-cage with the following parameters illustrated in Table II and Table III. Induction motor equivalent circuit is shown in Fig. 2. R_2 and X_2 are set to zero, if a single-cage induction motor is used. Induction motor load is

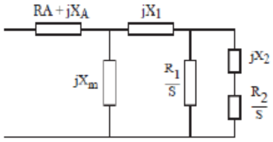


FIG. 2. Induction motor equivalent circuit.

represented by an asynchronous machine in Digsilent.

D. Transient Voltage Intensity Index

Short-term voltage stability associates with maintaining bus voltages stable following the large disturbances caused by generator tripping, short-circuit fault, loss of heavy load and etc. Consequently, delayed voltage recovery, undesirable transient voltage violation, fast voltage collapse may happen. NERC/WECC planning standards are used to effectively quantify voltage dip[26].

This paper proposes transient voltage intensity index (TVII) to measure transient voltage dip magnitude and its duration under a set of probable contingencies after clearing the disturbance (Eq. (1)). TVII with small value represents an acceptable transient voltage performance[11].

$$\mathrm{TVII} = \frac{\sum_{j=1}^{K} \sum_{j=t_{clearance}}^{T} \mathrm{TVVI}_{j,t}}{K \times (T - t_{clearance})} \tag{1}$$

where T is set to 2 (s), $t_{clearance}$ is assumed to be 0.3 (s), K is the whole number of buses in system (e.g. 39), TVVI is the *transient voltage violation index* given as follows:

$$\mathrm{TVVI}_{j,t} = \begin{cases} \frac{|V_{j,t} - V_{j,0}|}{V_{j,0}}, if \ \frac{|V_{j,t} - V_{j,0}|}{V_{j,0}} \geq 20\% \\ 0, \qquad \text{otherwise} \end{cases}, \tag{2}$$

$$\forall t \in [t_{clearance}, T]$$

According to NERC/WECC planning standards, the maximum deviation of voltage is set on 20%[26]. The simulation step size to evaluate the above indexes is set on 0.0025 (s).

E. Risk-Based Criterion

Contrary to the most of previous studies which only a single contingency has been considered for placement of dynamic VAR resources, this paper makes allowances for several contingencies taking into account their percentage of probability and transient voltage intensity both. Risk index (Risk) is used to assess transient voltage performance under multiple contingencies[11].

$$\mathrm{Risk} = \sum_{c=1}^{N} \mathrm{TVII}_c \times P_c \tag{3}$$

F. Trajectory Sensitivity

Generally, power system behavior can be determined by differential-algebraic equation[27]:

$$\dot{x} = f(x, y, \lambda) \tag{4}$$

$$0 = g(x, y, \lambda) \tag{5}$$

where x are dynamic state variables such as generator fluxes, angles and velocities, y are algebraic state variables such as load bus voltage angles and magnitudes, λ is the variable system parameter, e.g., fault clearing time, line reactances.

The flows of x and y are formalized, respectively, as[28]:

$$x(t) = \phi_x(x_0, t, \lambda) \tag{6}$$

$$y(t) = \phi_y(x_0, t, \lambda) \tag{7}$$

Sensitivities of flows are calculated considering initial condition variation and Taylor's series expansion of Eq. (6) and Eq. (7). Disregarding higher order terms and using Eq. (6) and Eq. (7) gives:

$$\Delta x(t) = \frac{\partial x(t)}{\partial \lambda} \Delta\lambda \equiv x_\lambda(t) \Delta\lambda \tag{8}$$

$$\Delta y(t) = \frac{\partial y(t)}{\partial \lambda} \Delta\lambda \equiv y_\lambda(t) \Delta\lambda \tag{9}$$

The sensitivities x_λ and $y_\lambda$can be evaluated in a straightforward way rather than doing such a complicated procedure:

$$x_\lambda \equiv \frac{\partial x}{\partial \lambda} \approx \frac{\Delta x}{\Delta \lambda} = \frac{\phi_x(x_0, t, \lambda + \Delta\lambda) - \phi_x(x_0, t, \lambda)}{\Delta\lambda} \tag{10}$$

$$y_\lambda \equiv \frac{\partial y}{\partial \lambda} \approx \frac{\Delta y}{\Delta \lambda} = \frac{\phi_y(x_0, t, \lambda + \Delta\lambda) - \phi_y(x_0, t, \lambda)}{\Delta\lambda} \tag{11}$$

where $\Delta\lambda$ is very small.

The trajectory sensitivity can be obtained from[28] and[29] in details. In this paper, Sensitivity index (S) is utilized based on trajectory sensitivity analysis to select the candidate locations for SVC. Along with, choosing the suitable candidate buses will reduce the size of SVC. Sensitivity of the changes in bus transient voltage magnitudes under multiple contingencies, e.g. Risk, with respect to reactive power injection at bus j[11]:

$$S_j = \frac{RI(C_j) - RI(\Delta C + C_j)}{\Delta C} \tag{12}$$

TABLE II. Clod large induction motor data

R_A (ohms)	X_A (ohms)	X_m (ohms)	R_1 (ohms)	X_1 (ohms)	R_2 (ohms)	X_2 (ohms)	H (s)
0.0138	0.083	3	0.055	0.053	0.0115	0.055	1

TABLE III. Clod small induction motor data

R_A (ohms)	X_A (ohms)	X_m (ohms)	R_1 (ohms)	X_1 (ohms)	R_2 (ohms)	X_2 (ohms)	H (s)
0.0369	0.1318	2.396	0.0645	0.0645	0.0489	0.321	0.6

ΔC has a small portion, e.g. 10 MVAR.
S_j represents the importance of bus j for SVC installation so that it plays a crucial role for enhancing the short-term voltage stability following multiple contingencies. Load buses with larger S_j will be chosen as candidate for SVC placements in the optimization procedure.

III. MATHEMATICAL FORMULATION

A. Objective Function

In this paper, the objective function is decomposed into two optimization sub-problems. A multi-objective optimization problem (MOP) can be defined as:

$$\text{Objective Function} = \text{minimize}[f_1(u), f_2(u)] \tag{13}$$

where u are decision variables which include SVC placement and size.

The first objective f_1 is the whole investment costs compromising installation and purchasing costs of SVC in this project, given by:

$$f_1 = \sum_{j=1}^{W} \text{Cost}_{\text{purchase}} \times C_j \times b_j + \sum_{j=1}^{W} b_j \times \text{Cost}_{\text{install}} \tag{14}$$

where b_j stands for binary decision variable expressing existence or nonexistence of SVC in bus j (1 or 0), $\text{Cost}_{\text{purchase}}$ and $\text{Cost}_{\text{install}}$ are \$0.05 million/MVAR and \$1.5 million respectively[30], W is the whole number of candidate buses for SVC deployment which is obtained using Eq. (12).

The second objective f_2 indicates the undesirable behavior of transient voltage under multiple probable contingencies, which were introduced by Risk (Eq. (3)) previously. It should be noticed that f_2 cannot be calculated during optimization procedure; it is calculated by time-domain simulation after SVC optimal deployment in the system.

In this MOP model when there is a conflict between objectives during the optimization procedure, maximization of f_2 and minimization of f_1 will be selected as a final solution.

B. Equality Constraint

The equality constraints include power flow balance equations which must satisfy active and reactive power balance at each bus:

$$P_g - P_L = P(V, \theta) \tag{15}$$

$$Q_g - Q_L = Q(V, \theta) \tag{16}$$

where P and Q are power flow equations, θ denotes the voltage angle, P_G and Q_G are active and reactive power generation, P_L and Q_L are active and reactive power load.

C. Inequality Constraint

Power flow limit of line is shown in Eq. (17), generator output capacities are represented in Eq. (18) and Eq. (19), bus voltage magnitude limits are defined in Eq. (20), the lower and upper bounds for SVC are represented in Eq. (21).

$$S_l(V, \theta) \leq S_{l-\max} \tag{17}$$

$$P_{g-\min} \leq P_g \leq P_{g-\max} \tag{18}$$

$$Q_{g-\min} \leq Q_g \leq Q_{g-\max} \tag{19}$$

$$V_{\min} \leq V \leq V_{\max} \tag{20}$$

$$C_{\min} < C < C_{\max} \tag{21}$$

Moreover, rotor angle stability and short-term voltage stability are closely linked to each other. In some cases loss of synchronism of any generator in power system may lead to short-term voltage instability or collapse.

Therefore, the rotor angle must be checked via a certain threshold to ensure rotor angle stability. Rotor angle between the two groups of generators should not deviate from 180 degrees.

IV. SOLUTION METHOD

A. Genetic Algorithm

Genetic Algorithms (GAs) are a search heuristic that are subclass of a larger group called evolutionary algorithms (EA). Genetic Algorithm is a way of solving problems which were invented to simulate the mechanics of natural genetics. Genetics is about how biological properties inherit and transfer from generation to generation through chromosomes and genes; their operation is so that the superior and stronger genes and chromosomes have a greater chance to contribute to produce new individuals than the poorer ones. The basic operations of Genetic Algorithm are introduced in[31].

B. MATLAB And Digsilent Interface

Due to the excessive application of optimization techniques such as fuzzy logic, genetic, and , the interface between MATLAB and Digsilent is provided. Usually, writing some numerical algorithms in Digsilent Programming Language (DPL) is difficult. Hence, in some cases such as the use of fuzzy or neural functions, using MATLAB is preferred. For this purpose, various methods have been tested and finally using a linked text file is chosen as one of the best ways for MATLAB and Digsilent data exchange.

In order to optimize an objective function (optimization.dz) coded in DPL, a genetic algorithm written in MATLAB (GA.m) is utilized; the following procedures describe the data exchange between these two software:

1. Firstly, optimization.dz program inserts the code 0 into Link.txt, which means optimization.dz is still working and GA.m has not started yet.
2. optimization.dz inserts the column vector $\begin{pmatrix} 1 \\ \text{nvars} \\ \text{population\_size} \\ \text{Generation} \end{pmatrix}$ into Link.txt, where nvars is the number of chromosome used in genetic algorithms. Code 1 means it is the time for GA.m to be started.
3. GA.m inserts code 2 and the column vector of variables, which its row number is equal to nvars, into Link.txt. Code 2 means GA.m has done its work and is waiting for optimization.dz output.
$$\left(\begin{matrix} 2 \\ \begin{pmatrix} X_1 \\ X_1 \\ . \\ . \\ X_{nvars} \end{pmatrix} \end{matrix} \right) = \begin{pmatrix} 2 \\ X_1 \\ X_1 \\ . \\ . \\ X_{nvars} \end{pmatrix}$$
4. optimization.dz starts its task upon seeing code 2 at the beginning of Link.txt. The objective function is calculated via variables given in Link.txt. Then, optimization.dz inserts code 3 and objective function value in the form of a column vector $\begin{pmatrix} 3 \\ OF \end{pmatrix}$ into Link.txt, where 3 means a temporary end of optimization.dz task and GA.m will start again.
5. If the maximum number is not reached, go back to Step 3, otherwise go to the next step.
6. GA.m comes to an end, so GA.m understands the iteration number is reached via Link.txt.
7. optimization.dz understands the termination by seeing the code 4 in Link.txt.

C. Computation Process

The proposed methodology is summarized in Fig. 3. The total calculation process is divided into 8 stages. In stage 1, the network model, certain contingencies taking into account their percentage of probability are considered as input. In stage 2, the candidate buses for SVC installation are chosen using Eq. (12). Only the five load buses with larger will be chosen as candidate buses for optimization process. Stage 3 is started with choosing random initial population size. In stage 4, the fitness of each chromosomes in the population is evaluated. In stage 5, the new population is generated according to Step 3 in Genetic Algorithm. In stage 6, for each generated offspring, the objective function (f_1) is calculated according to Eq. (14), and then time-domain simulation is used to calculate (f_2) using Eq. (3). In stage 7, the new generated population is used for doing subsequent steps of the algorithm. In stage 8, if the termination condition is provided, the calculation will be stopped. Otherwise, the calculation process is repeated from stage 3 until the termination condition is satisfied.

V. SOLUTION RESULT AND DICUSSION

In this paper, the New England 10-machine 39-bus test system is used to verify the performance of the proposed methodology for the optimal SVC allocation. The one-line diagram of this test system is shown in Fig. 4, its

TABLE IV. TVII and risk before SVC instalation

Bus No.	8	15	21	23	25
TVII (constant load model)	0.7773	0.8439	0.7087	0.6724	0.6822
TVII (CLOD model)	10.2671	5.2024	3.0613	2.5358	2.4975
TVII (wind farm)	11.1811	5.71	3.8447	3.3107	3.0777

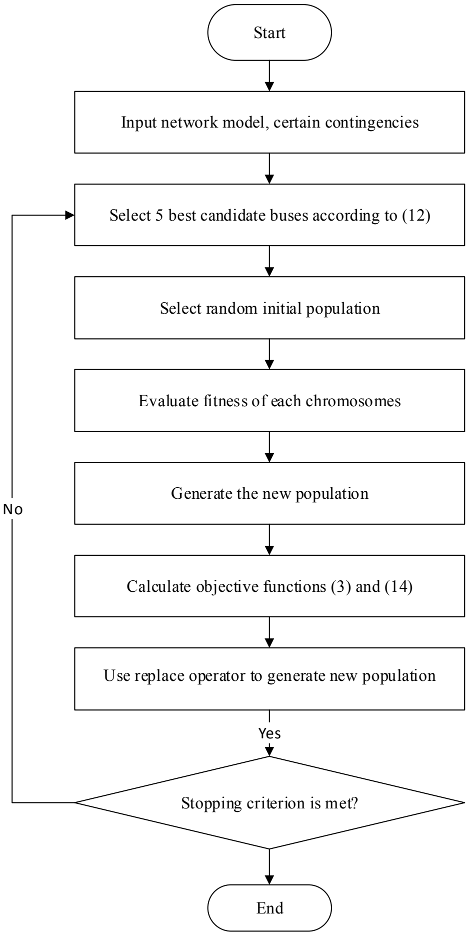


FIG. 3. Computation flowchart.

total reactive and active loads of the system are 2555.6 (MVAR) and 6150.5 (MW) respectively; the power system data is available in[32] in details.

The time domain simulation is solved in Digsilent Power Factory 15.1.7, the Genetic Algorithm (GA) is performed in MATLAB 2011.*a*, and a Link.txt is used to interface Digsilent and MATLAB.

A. Short-term Voltage Stability Performance

As mentioned in Section II D, the short-term voltage stability is quantified using TVII. In this paper, several certain contingencies with their probabilities are considered to calculate TVII and the second objective function (e.g. Risk). Five 3-phase short-circuit faults are occurred in the various regions of the network. The faults are happened at buses 8, 15, 21, 23, and 25 buses. These three-phase faults are occurred in 0.19 (s) and cleared at 0.3 (s), with the probability of 20% for all of them.

Three time-domain simulations are run and compared with each other to show the effects of load dynamics and renewable energy sources such as wind energy on voltage performance. For this purpose, at first, the constant power load is considered. Secondly, the composite load model is used. Finally, short-term voltage stability is measured with the presence of 300 (MW) wind farm.

At first, transient studies are done separately for each contingency. TVII values for constant power load, CLOD, and wind farm are illustrated in Table IV; Risk values for these situations are 0.7369, 4.712, and 5.4248 respectively. Accordingly, using dynamic load model and wind farm influence the short-term voltage instability significantly rather than using constant power load in system.

Voltage responses in time frame of $0-2$ (s) for bus 21 under the fault at bus 21 is shown in Fig. 5 comparing the systems voltage performance with constant power load, CLOD, and wind farm. As Fig. 5 shows, the fast dynamic loads (such as induction motors) respond quickly to voltage changes due to their low inertia; moreover, they consume more reactive power in comparison to constant power load. Thats why when the CLOD model is used, voltage recovers slowly. In terms of the constant power load model, bus voltages immediately recover to the normal condition. Also, wind farm installation has a significant impact on voltage stability due to its random behavior and uncertainty; In addition to voltage slow recovery, the voltage drops between $0.7-0.9$ (s). Generator rotor angles shown in Fig. 6 for the system with CLOD (Fig. 6a) and wind farm (Fig. 6b) under fault at bus 21; none of the generators lose their synchronism, this is also true for faults at buses 8, 15, 23 and 25. This verifies the rotor angle stability in the system.

The use of SVC as dynamic support to improve short-term voltage stability will be investigated in the following sections. For this purpose, two cases are investigated: *Case A)* system without wind farm *Case B)* system with wind farm. In these cases, the CLOD model will be used.

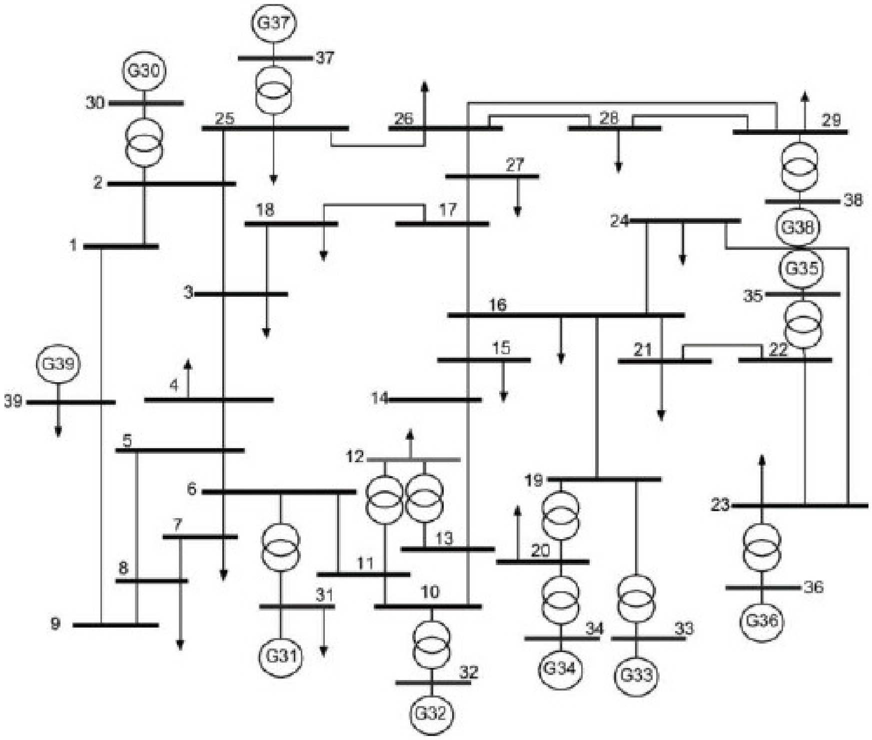


FIG. 4. One-line diagram of the New England 10-machine 39-bus system.

TABLE V. Selected SVC (*Case A*)

Bus No.	3	4	16	18	23	Total
Size (MVAR)	0	59	0	34	59	152

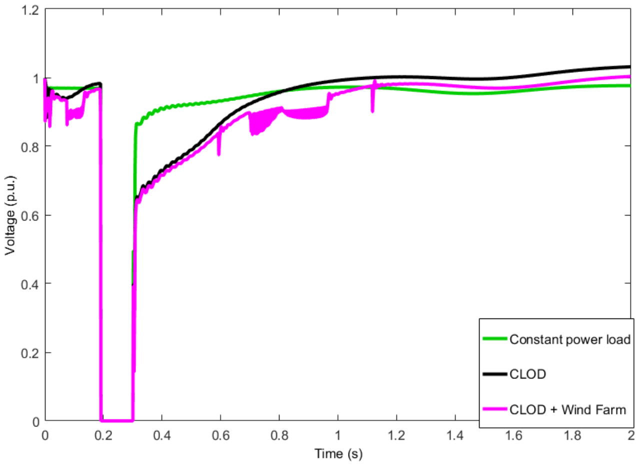


FIG. 5. Voltage performance comparison for bus 21 under the fault at bus 21.

B. Candidate Buses Selection

As mentioned in Section II F, only 17 load buses should be considered to calculate the S_j. The largest five candidate buses for SVC installation are determined for two cases.

Case A) buses 3, 4, 16, 18, and 23.

Case B) buses 4, 15, 16, 18, and 20.

The results are illustrated in Fig. 7 for *Case A* and *Case B*.

C. SVC Placement Results

In this paper, the MOP is calculated using Genetic Algorithm and codes written in DPL for SVC installation to minimize the objective functions. The population size and generation in Genetic Algorithm are set to 6 and 18 respectively.

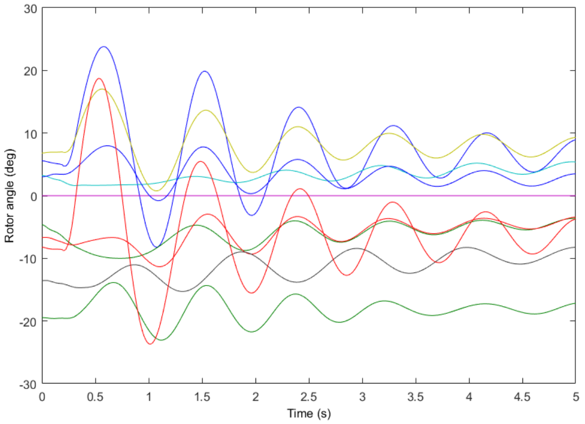
Case A) The size of SVCs with their locations are shown in Table V for system without wind farm. The whole size is 152 (MVAR). The whole investment costs (Eq. (14)) is $12.1 million. The TVII values for each of the certain contingencies are shown in Table VI. As a result, Risk is 2.2094. To verify the short-term voltage improvement, Table VI and Table IV can be compared. By reason of SVC installation, the Risk is reduced by 53.12%.

TABLE VI. $\text{TVII}_{\text{after}}$ $\text{SVC}_{\text{installation}}$ (*Case A*)

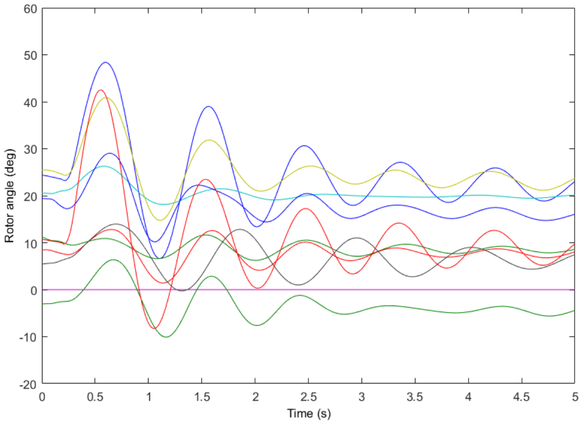
Bus No.	8	15	21	23	25
TVII (CLOD)	5.1750	2.3188	1.4174	1.2444	0.8914

TABLE VII. Selected SVC (*Case B*)

Bus No.	4	15	16	18	20	Total
Size (MVAR)	44	79	0	0	69	192

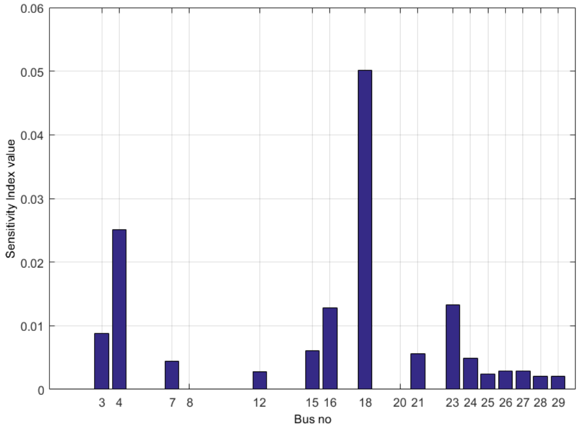


(a)System with CLOD load model.

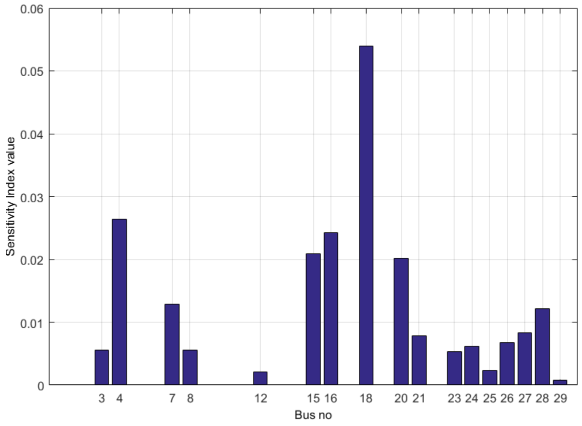


(b)System with wind farm.

FIG. 6. Generator rotor angle response under the fault at bus 21.



(a)System with CLOD load model.



(b)System with wind farm.

FIG. 7. Sensitivity value for all load buses.

Case B) The optimal allocation of SVC is shown in Table VII with details for system with wind farm. The total size is 192 (MVAR). The TVII values for 5 contingencies are given in Table VIII, and the Risk is 2.49. Comparing Table IV and Table VIII represents the 54% reduction on Risk. The whole investment costs is $14.1 million.

Voltage performances $(0 - 2\ (s))$ for bus 21 under the fault at bus 21 are shown in Fig. 8 and Fig. 9 for *Case A* and *Case B* respectively. It can be seen that by using SVC as dynamic support, the bus voltages recover fast so that the short-term voltage stability will improve.

VI. CONCLUSIONS

In this paper, a new methodology has been proposed to find optimal allocation and sizing of SVC due to objective functions minimization. In this regard, a Genetic Algorithm-based algorithm and DPL codes

TABLE VIII. TVII$_{\text{after}}$ SVC$_{\text{installation}}$ (*Case B*)

Bus No.	8	15	21	23	25
TVII (CLOD)	5.8706	2.6429	1.6181	1.4146	0.9889

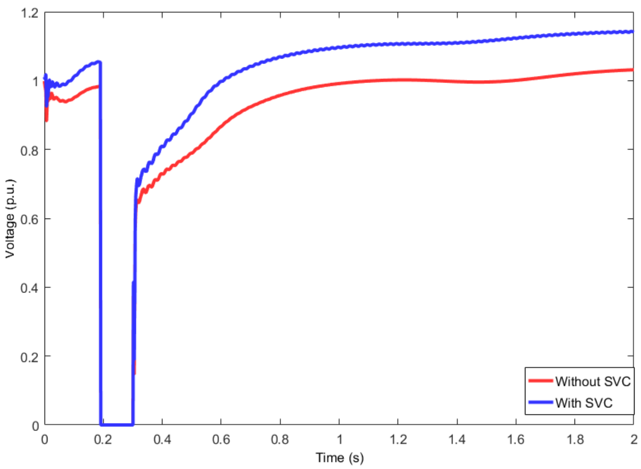


FIG. 8. Voltage response for bus 21 with and without SVC (*Case A*).

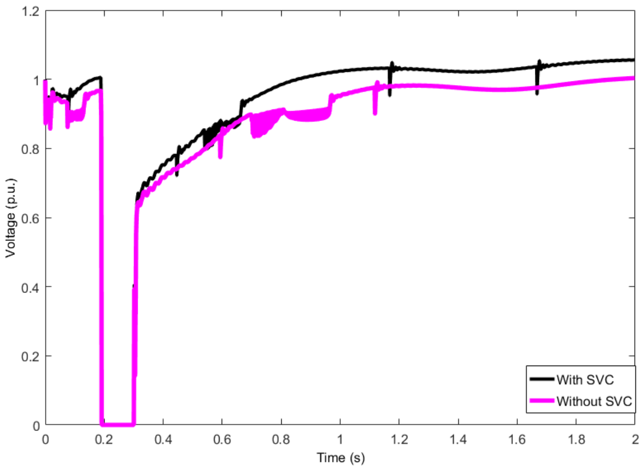


FIG. 9. Voltage response for bus 21 with and without SVC (*Case B*).

have been proposed. At first, the impacts of using wind farm and load dynamics such as induction motor loads on short-term voltage stability are investigated considering multiple probable contingencies; the degree of transient voltage performances is measured by TVII. Then, a trajectory sensitivity based analysis is applied to find the best candidate buses for SVC installation which can effectively reduce the size of SVC. As a fast dynamic reactive power supporter, SVC plays an important role to recover the bus voltages very fast after being subjected to disturbances. This study is open to utilize other dynamic VAR sources such as UPFC and STATCOM. Also, the proposed method can be developed for power systems with another dispersed power generation such as photovoltaic systems, fuel cells, and etc considering various combination of fast dynamic loads such as HVDC links, induction arc furnace, and etc to investigate their impacts on short-term voltage stability.

REFERENCES

[1] S. Wildenhues, J. L. Rueda, and I. Erlich, "Optimal allocation and sizing of dynamic var sources using heuristic optimization," *IEEE Transactions on Power Systems*, Vol. 30, No. 5, pp. 2538-2546, 2015.

[2] C. F. Yang, G. G. Lai, C. H. Lee, C. T. Su, and G. W. Chang, "Optimal setting of reactive compensation devices with an improved voltage stability index for voltage stability enhancement," *International Journal of Electrical Power & Energy Systems*, Vol. 37, No. 1, pp. 50-57, 2012.

[3] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, et al., "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions," *IEEE transactions on Power Systems*, Vol. 19, No. 3, pp. 1387-1401, 2004.

[4] A. Phadke, M. Fozdar, and K. Niazi, "A new multi-objective fuzzy-GA formulation for optimal placement and sizing of shunt FACTS controller," *International Journal of Electrical Power & Energy Systems*, Vol. 40, No. 1, pp. 46-53, 2012.

[5] C. D. Vournas and E. G. Potamianakis, "Investigation of short-term voltage stability problems and countermeasures," in *in Power Systems Conference and Exposition, 2004. IEEE PES*, pp. 385-391, 2004.

[6] J. D. De Leon and C. W. Taylor, "Understanding and solving short-term voltage stability problems," in *in Power Engineering Society Summer Meeting, 2002 IEEE*, pp. 745-752, 2002.

[7] W. D. Rosehart, C. A. Canizares, and V. H. Quintana, "Effect of detailed power system models in traditional and voltage-stability-constrained optimal power-flow problems," *IEEE Transactions on Power Systems*, Vol. 18, No. 1, pp. 27-35, 2003.

[8] J. Mantovani and A. Garcia, "A heuristic method for reactive power planning," *IEEE Transactions on Power Systems*, Vol. 11, No.1 , pp. 68-74, 1996.

[9] B. B. Chakrabarti, D. Chattopadhyay, and C. Krumble, "Voltage stability constrained Var planning-a case study for New Zealand," in *in Power Engineering, 2001. LESCOPE'01. 2001 Large Engineering Systems Conference on*, pp. 86-91, 2001.

[10] B. Sapkota and V. Vittal, "Dynamic VAr planning in a large power system using trajectory sensitivities," *IEEE Transactions on Power Systems*, Vol. 25, No. 1, pp. 461-469, 2010.

[11] Y. Xu, Z. Y. Dong, K. Meng, W. F. Yao, R. Zhang, and K. P. Wong, "Multi-objective dynamic VAR planning against short-term voltage instability using a decomposition-based evolutionary algorithm," *IEEE Transactions on Power Systems*, Vol. 29, No. 6, pp. 2813-2822, 2014.

[12] G. Geng, V. Ajjarapu, and Q. Jiang, "A hybrid dynamic optimization approach for stability constrained optimal power flow," *IEEE Transactions on Power Systems*, Vol. 29, No. 5, pp. 2138-2149, 2014.

[13] Y. Xu, Z. Y. Dong, C. Xiao, R. Zhang, and K. P. Wong, "Optimal placement of static compensators for multi-objective voltage sta-

bility enhancement of power systems,"*IET Generation, Transmission & Distribution*, Vol. 9, No. 15, pp. 2144-2151, 2015.

[14] G. N. Kumar and M. S. Kalavathi, "Cat swarm optimization for optimal placement of multiple UPFCs in voltage stability enhancement under contingency,"*International Journal of Electrical Power & Energy Systems*, Vol. 57, pp. 97-104, 2014.

[15] P. Prabhakar and A. Kumar, "Voltage stability boundary and margin enhancement with FACTS and HVDC,"*International Journal of Electrical Power & Energy Systems*, Vol. 82, pp. 429-438, 2016.

[16] V. Akhmatov and P. B. Eriksen, "A large wind power system in almost island operation-A Danish case study,"*IEEE Transactions on power systems*, Vol. 22, No. 3, pp. 937-943, 2007.

[17] A. Tiwari and V. Ajjarapu, "Optimal allocation of dynamic VAR support using mixed integer dynamic optimization,"*IEEE Transactions on Power Systems*, Vol. 26, No. 1, pp. 305-314, 2011.

[18] C. Han, A. Q. Huang, M. E. Baran, S. Bhattacharya, W. Litzenberger, L. Anderson, et al., "STATCOM impact study on the integration of a large wind farm into a weak loop power system,"*IEEE Transactions on energy conversion*, Vol. 23, No. 1, pp. 226-233, 2008.

[19] M. H. Bollen, "Voltage recovery after unbalanced and balanced voltage dips in three-phase systems,"*IEEE Transactions on Power Delivery*, Vol. 18, No. 4, pp. 1376-1381, 2003.

[20] B. R. Williams, W. R. Schmus, and D. C. Dawson, "Transmission voltage recovery delayed by stalled air conditioner compressors,"*IEEE Transactions on Power Systems*, Vol. 7, No. 3, pp. 1173-1181, 1992.

[21] A. Hammad and M. El-Sadek, "Prevention of transient voltage instabilities due to induction motor loads by static VAR compensators,"*IEEE Transactions on Power Systems*, Vol. 4, No. 3, pp. 1182-1190, 1989.

[22] F. De Mello and J. Feltes, "Voltage oscillatory instability caused by induction motor loads,"*IEEE transactions on power systems*, Vol. 11, No. 3, pp. 1279-1285, 1996.

[23] I. R. Navarro, O. Samuelsson, and S. Lindahl, "Influence of normalization in dynamic reactive load models,"*IEEE Transactions on Power Systems*, Vol. 18, No. 2, pp. 972-973, 2003.

[24] T. Van Cutsem and C. Vournas, *Voltage stability of electric power systems* Vol. 441: Springer Science & Business Media, 1998.

[25] P. Siemens, "PSS/E 33.0 Program Application Guide,"ed: May, 2011.

[26] D. Shoup, J. Paserba, and C. Taylor, "A survey of current practices for transient voltage dip/sag criteria related to power system stability,"in *in Power Systems Conference and Exposition, 2004. IEEE PES*, pp. 1140-1147, 2004.

[27] L. G. Perez, A. J. Flechsig, and V. Venkatasubramanian, "Modeling the protective system for power system dynamic analysis,"*IEEE Transactions on Power Systems*, Vol. 9, No. 4, pp. 1963-1973, 1994.

[28] I. A. Hiskens and M. Akke, "Analysis of the Nordel power grid disturbance of January 1, 1997 using trajectory sensitivities,"*IEEE Transactions on Power Systems*, Vol. 14, No. 3, pp. 987-994, 1999.

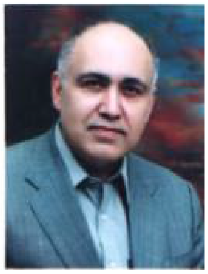
[29] I. A. Hiskens and M. Pai, "Trajectory sensitivity analysis of hybrid systems,"*IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, Vol. 47, No. 2, pp. 204-220, 2000.

[30] H. Liu, "Planning reactive power control for transmission enhancement,"Iowa State University, 2007.

[31] K. F. Man, K. S. Tang, and S. Kwong, "Genetic algorithms: concepts and applications [in engineering design],"*IEEE transactions on Industrial Electronics*, Vol. 43, No. 5, pp. 519-534, 1996.

[32] J. Chow and G. Rogers, "Power system toolbox, "*Cherry Tree Scientific Software, [Online] Available: http://www.ecse.rpi.edu/pst/PST.html*, Vol. 48, p. 53, 2000.

Parnian Fakhrooeian was born in Shiraz, Iran. She received her B.S. degree in Electrical Engineering from Shahid Beheshti University, Tehran, Iran, in 2014, and her M.S. degree in Electrical Engineering from Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran, in 2016. Her current research interests include FACTS devices, short-term voltage instability, reactive power planning and renewable energy.



Mehrdad Abedi received the B.Sc., M.Sc. and Ph.D. degrees from Tehran University, Iran, London University, UK, and Newcastle University, UK, in 1970, 1973, and 1977, respectively. He worked for G.E.C. (U.K) until 1978. Since then he joined EE Dept of Amirkabir University (Tehran, Iran) where he is now professor and head of the Center of Excellence on Power System. Prof. Abedi has published more than 20 books and 140 papers in journals and conferences. He is distinguished professor in Iran and is prize winner for two outstanding books. He is also member of Iranian Academy of Science and member of CIGRE. His main interest is electrical machines and power systems modeling, operation and control.

Peyman Karimyan received the B.S. degree from Iran University of Science and Technology, Tehran, Iran, in 2011, and the M.S. degree from Amirkabir University of Technology, Tehran, Iran, in 2013, both in electrical engineering. He is currently working towards PhD degree at the Amirkabir University. His research interests include power systems operation, control and protection.