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Designing PSS and SVC Parameters simultaneously through the Improved Quantum Algorithm in the Multi-machine Power System

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Abstract
As to the importance of power system performance in terms of quality, and stability, using flexible AC transmission system (FACTS) devices in power systems and coordinating these devices through power system stabilizers (PSSs) have gained a great acceptance. Accordingly, the problem of coordinated design of PSS and static var compensator (SVC) parameters in multi-machine power systems is introduced and solved through the improved quantum method. In previous studies, PSS is designed for damping small-signal oscillations of the power system. To damp large-signal oscillations, PSS should be designed in accordance with other devices like SVC. Therefore to reach overall stability of power system, the quantum-inspired evolutionary algorithm is applied here to determine PSS parameters and SVC in a coordinated manner. This proposed method is applied in determining PSS parameters and SVC of Kundur's four-machine power systems and the New England 39-bus system. Simulation results reveal the effective performance of this proposed method in comparison with particle swarm optimization (PSO) and bacteria foraging optimization (BFO) methods.

Index Terms: PSS; Quantum-Inspired Evolutionary Algorithm; Stability; SVC.

طراحی همزمان پارامترهای PSS و SVC با استفاده از روش کوانتوم بهبود یافته جهت ارتقای پایداری سیستم قدرت چند ماشینه

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خلاصه: امروزه با توجه به اهمیت ارتقای عملکرد سیستم قدرت از دیدگاه کیفیت توان و پایداری، استفاده از ادوات FACTS در شبکه‌های قدرت، و هماهنگ سازی این ادوات با پایدارسازهای سیستم قدرت مورد توجه قرار گرفته است. با توجه به این مسأله، در این مقاله مسأله طراحی هماهنگ پارامترهای PSS و SVC در سیستم‌های قدرت چندماشینه معرفی گردیده و با روش کوانتوم حل گردیده است. با وجود این که PSS برای میراسازی نوسانات سیگنال کوچک سیستم قدرت طراحی می‌شود، این وسیله برای میراسازی نوسانات سیگنال بزرگ باید با سایر تجهیزات از جمله SVC به صورت هماهنگ طراحی شود. لذا برای پایداری بهتر سیستم قدرت در این مقاله پارامترهای PSS و SVC به صورت هماهنگ با استفاده از الگوریتم QEA به دست آمده است. روش ارائه شده برای تعیین پارامترهای PSS و SVC بر روی سیستم‌های چهار ماشینه کندور و ۳۹ باس نیوانگلند قسمت شده است. نتایج شبیه‌سازی مؤید برتری روش پیشنهادی نسبت به روش‌های الگوریتم بهینه‌سازی ازدحام ذرات و الگویتم بهینه‌سازی غذایابی باکتریایی می‌باشد.

کلمات کلیدی: الگوریتم تکاملی کوانتوم ،پایداری، PSS، SVC.

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1. Introduction

The problem of power system stability is one of the important issues in power systems. Small-signal disturbances like power generation load change and large-signal disturbances including single phase and three phase short circuit in power systems cause and promote instability in power systems. In this case, if there exists no control to damp these oscillations, they might lead to a blackout in a great part of the power system. The power system stabilizer (PSS) is a highly efficient method to damp these oscillations introduced by [1]. PSS establishes the damping torque required by the power system by adding signals to the generator excitation control, while, PSS cannot damp the large-signal oscillations in the power system.

With the rapid advances made in power electronic technology, flexible ac transmission system (FACTS) devices are being applied to control the reactive power of the power system [2]. Furthermore, FACTSs can be applied in improving the stability (transient and dynamic) of the power systems and overcome the power transmission limits of the same [3]. Although, the main task of FACTS devices is not to improve the stability or to overcome the power transmission limits, they can be applied in improving the stability of power system. Static VAR Compensator (SVC) is one of the devices applied in oscillations damping in the power system. SVC, as one of the FACTSs' devices that control the reactive power and voltage, which is applied as a means to assist PSS damping the internetwork oscillations [4].

Considering the fact that PSS is designed based on the linear model in one operating point of power system, it may have no acceptable performance in other operating points. There exist studies suggesting application of new controlling techniques like modern and intelligent control (e.g., neural networks) in improving the PSS performance [5]. To design PSS, evolutionary algorithms have already been applied in a great number of studies [6-11] to determine PSS and FACTS controller parameters. For thus purpose algorithms like Genetic Algorithm (GA) [6], Particle Swarm Optimization (PSO) [7], Bacteria Foraging Optimization (BFO) [8], Imperialist Competition Algorithm (ICA) [9], Firefly Algorithm (FA) [10] and Cultural Algorithm (CA) [11] are applied. These algorithms are applied in solving optimization problem; however, their efficiency and problem-solving quality depends on the appropriate adjustment of the control parameters in given system, requiring much time and energy if number of parameters is great. Algorithms like PSO and BFO would face local optimization problems [12]. The Quantum Calculations is introduced by Benioff and [13]-[14]. Due to such conceptual calculations, quantum computers and quantum algorithms have gained more importance. Applying Quantum Calculations concept for improving the efficiency of evolutionary algorithms to regular computers has led to QEAs development [15-16]. Here, the QEA is applied to design PSS and SVC parameters in order to overcome the drawbacks concerning the aforementioned algorithms.

2. Problem Statement

In order to convert this newly proposed design into a mathematical model, power system should be modeled in a dynamic manner. Accordingly, PSS, SVC and the generator, must be modeled in the same manner.

2.1. PSS and Generator Modeling

Consider a power system with n generators, where the Dynamic model of the i^{th} machine in terms of fifth order differential equations is presented in (1- 5), [3]:

$$\frac{d\delta_i}{dt} = \omega_0 . \omega_i \tag{1}$$

$$\frac{d\omega_i}{dt} = -\frac{1}{2H_i}\left[P_{mi} - P_{ei} - D_i \omega_i\right] \tag{2}$$

$$\frac{de'_{di}}{dt} = \frac{1}{T'_{qoi}}\left[-e'_{di} - (x_{qi} - x'_{di})I_{qi}\right] \tag{3}$$

$$\frac{de'_{qi}}{dt} = \frac{1}{T'_{doi}}\left[E_{fdi} - e'_{qi} - (x_{di} - x'_{di})I_{di}\right] \tag{4}$$

$$\frac{df_{fdi}}{dt} = -\frac{1}{T_{Ai}}(E_{fdi} - E_{fdio}) - \frac{K_{Ai}}{T_{Ai}}(V_{ti} - V_{tio}) \tag{5}$$

where, δ, ω, H, P_m, P_e, D, e'_d, e'_q, x_d, x'_d, I_d, E_{fd}, T'_{do}, K_A, T_A and V_t are the angle, the angular velocity of rotor, inertia constant, mechanical input power, electrical output power, damping coefficient, the internal voltage of d- and q-axis, synchronous and transient reactance of d- and q-axis, the current of armature's d-axis and q-axis, excitation voltage, d-axis transient time constant, the gain and time constant of excitation and terminal voltage of the generator, respectively.

The classic PSS has a lead-lag structure as shown in Fig. (1). Because PSS should establish an electrical torque in the phase, lead-lag block is applied in PSS with charges in velocity. The block removing the effect of steady state acts as a high-pass filter with a large time constant, T_w allows the corresponding signals to oscillations, W_r to pass without being changed. The stabilizer gain K_s determines the amount of damping caused by the PSS.

2.2. SVC

SVC is one of the most important FACTS devices being applied for many years due to its technical and economical advantages in solving the voltage dynamic. Precision, accessibility and quick response of SVC, compared to classic parallel (shunt) compensator, has changed it into a highly efficient device in controlling the voltage of transient and steady states [2]. As observed in Fig. (2), a PI controller is set between the capacity and inductive currents to determine the SVC reactor current expressed as follows:

$$\dot{B} = \left(K_P + \frac{K_i}{S} \right) * \left(V_{SVC} - V_{SVC,rfs} \right) \qquad (6)$$

where, K_p and K_i are the proportional and integrator gains of the controller, respectively [4].

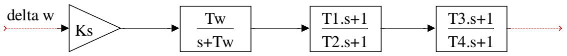

Fig. (1): Power system stabilizer [2]

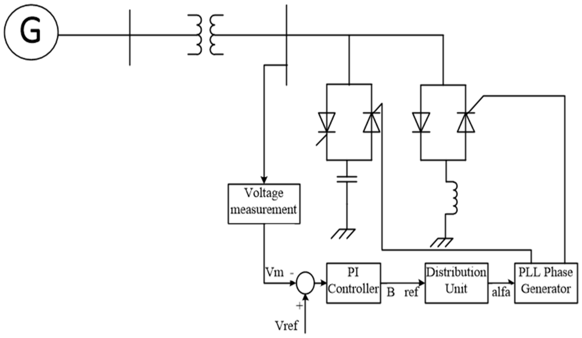

Fig. (2): SVC structure [4]

2.3. Proposed objective function

To design PSS and SVC parameters in a simultaneous manner, the following objective function is applied [16]. In (7) $\Delta\omega_i$ is the deviation of rotor speed of i^{th} generator. The proposed Integral of Time Multiplied by Absolute Error (ITAE) function is applied in obtaining the optimal control parameters of SVC and PSS as follows:

$$\begin{aligned}
&\min OF = \sum_{i=1}^{n} \int_{t_1=0}^{t_2=t_{sim}} t.[|\Delta\omega_i|]dt \\
&K_{pss,i}^{min} \le K_{pss,i} \le K_{pss,i}^{max} \\
&T_{1,i}^{min} \le T_{1,i} \le T_{1,i}^{max} \\
&T_{2,i}^{min} \le T_{2,i} \le T_{2,i}^{max} \\
&T_{3,i}^{min} \le T_{3,i} \le T_{3,i}^{max} \qquad .\ (7) \\
&T_{4,i}^{min} \le T_{4,i} \le T_{4,i}^{max} \\
&K_{pt}^{min} \le K_{pt} \le K_{pt}^{max} \\
&K_{it}^{min} \le K_{it} \le K_{it}^{max}
\end{aligned}$$

The coordinated design of PSS and SVC is optimal, the gain K_{pss} and the coefficients T_1 through T_4 relate to PSS and the coefficients K_{pt} and K_{it} can be determined by solving the optimization problem. The numerical minimum and maximum range of K_{pss} and $T_{1,3}$ are obtained according to [3]-[4], where T_2 and T_4 are considered as $0.1<T_{2,4}<10$. The PI controller range in Fig. (2) is $0.1<K_{pt}<5$ and $100<K_{it}<500$ and the base power is considered according to [4].

3. Quantum-inspired Evolutionary Algorithm (QEA)

This algorithm, is one of the evolutionary algorithms acting based on quantum calculations. Quantum calculations is a field of research encompassing concepts like quantum computers [15].

The smallest data unit stored in a quantum computer is named the qubit. A qubit may get either of the states '1' or '0', shown as follows:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad (8)$$

where, α and β are the constituents of a compound number which determine the related possible range. $|\alpha|^2$ is the probability that the qubit would get the state 0, while $|\beta|^2$ indicates that the qubit would get '1' state. Given that a qubit would be either of the two states, the following is yield:

$$|\alpha|^2 + |\beta|^2 = 1 \qquad (9)$$

Therefore, an array of m qubits is expressed as follows:

$$\begin{bmatrix} \alpha_1 & \alpha_2 & .... & \alpha_m \\ \beta_1 & \beta_2 & .... & \beta_m \end{bmatrix} \qquad (10)$$

The execution steps of QEA are shown in Fig. (3) [16].

i. A valuing Q(0), for all the qubits of q_j^0 $j=(1,2,...,m)$ and a primary value $1/\sqrt{2}$ are given to all the qubits of α_{ji}^0 and β_{ji}^0 for $i=(1,2,...n)$, that is the observation probability of '0' equals that of '1'. In this case, m and n are the qubit vector length and qubits of response population number, respectively.

ii. A set of binary qubits of P(0) is generated from the qubits of Q(0). The qubits of $p(0)=\{x_1^0, x_2^0, ..x_m^0\}$ at t = 0 are generated subject to the values of, $|\alpha_i|^2$ and $|\beta_i|^2$ $i=(1,2,...m)$. A binary qubit x_j^0 $j=(1,2,...n)$ is a binary response with n length. A binary qubit from a qubit is generated through observation. To generate the binary bit x_i from a qubit

$\begin{bmatrix} \alpha_i \\ \beta_i \end{bmatrix}$, equation (10) is applied, while, U(.,.) is a function generating uniform random numbers, as follows:

$$x_i = \begin{cases} 0 & U(0,1) < \alpha_i^2 \\ 1 & \text{otherwise} \end{cases} . \qquad (11)$$

iii. The set of binary qubits acquired from step 2 is assessed by the objective function.

iv. The best response found among P(0) is stored in b.

v. The algorithm would be executed until the termination condition is met.

vi. Binary qubits of P(t) are generated by observing the states of Q(t-1).

vii. Qubit is updated by applying the qugate. Qugate is an operand applied in qubit and should resolve the restrictions of $|\alpha'|^2 + |\beta'|^2 = 1$ where, α' and β' are the updated values of qubit, respectively. The qugate applied in this study is displayed in (12) as follows:

$$U(\Delta\theta_i) = \begin{bmatrix} \cos(\Delta\theta_i) & -\sin(\Delta\theta_i) \\ \sin(\Delta\theta_i) & \cos(\Delta\theta_i) \end{bmatrix} . \qquad (12)$$

where, i=1, 2, …, n and $\Delta\theta_i$ is the rotation angle.

ix. In this phase, the best response found is stored in b.

3.1. Qugate

Qugate is an operand which updates the qubit value. The NOT, CNOT, Hadamard and rotation gates are Qugates. To update the qubit $[\alpha \quad \beta]^T$, we use the rotation gate in the given algorithm, is applied in accordance with (13) [15]:

$$[\alpha_i' \quad \beta_i']^T = \begin{cases} U(\Delta\theta_i)[\alpha_i \quad \beta_i]^T & \text{if} \alpha\beta > 0 \\ U(-\Delta\theta_i)[\alpha_i \quad \beta_i]^T & \text{otherwise} \end{cases} \qquad (13)$$

In (13), the value of $\Delta\theta$ is acquired from Table 1 and the qubit update can be observed in Fig. (4).

Table (1): The $\Delta\theta$ value in updating qubit [15]

x_i	b_i	f(x)<f(b)	-0.01π
0	0	False	0
0	0	True	0
0	1	False	0.01π
0	1	True	0
1	0	False	-0.01π
1	0	True	0
1	1	False	0
1	1	True	0

4. Simulation Results

To assess QEA performance to determine the PSS and SVC parameters, the obtained results are simulated through Kundur's four-machine power system and New England 39-bus system.

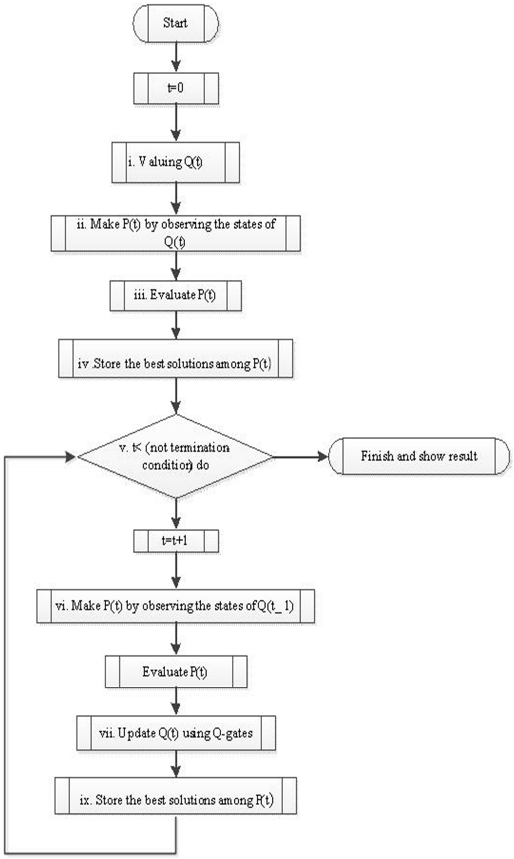

Fig. (3): QEA flowchart

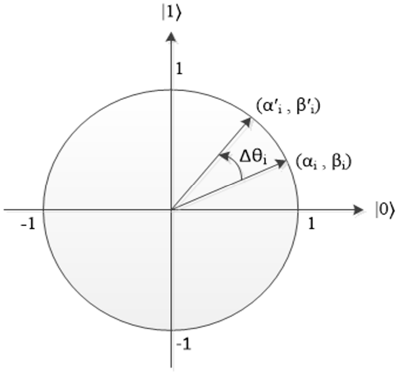

Fig. (4): Polar plan of gate rotation to update qubit [15]

4.1. Kundur's Four-Machine System

4.1.1. System Specifications

The Kundur's two-area system, Fig. (5) is applied to assess the proposed design. This system is composed of two identical and symmetric areas connected to each other by two 230 (KV) lines, with 220 (Km Lenght) [18]. To promote system function a VAR compensator is installed in the middle of the transmission line. This network is designed to assess the low-frequency electromechanical oscillations in specific. Each area includes two generators (one at Bus (1) and the other at Bus (6)) with identical rotors with nominal rate of 20 (KV), 900 (MVA). The parameters of generator 1 and 3 are optimized in the first and second areas, respectively.

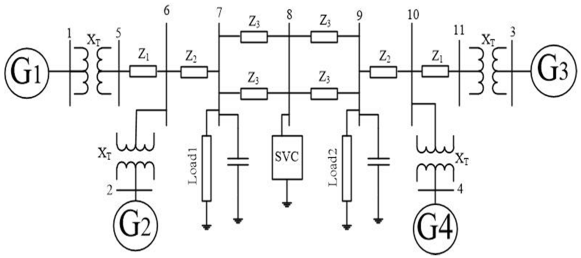

Fig. (5): The two area Kundur's four-machine, together with SVC system [4]

4.1.2. The Analysis of Kundur's Four-Machine System Simulation Results

To clarify the advantages of this proposed algorithm, the simulation for 100 (m-sec) symmetric three phase fault at bus 8 and PSS together with simultaneous presence of SVC and PSS is run and the signal values are compared through different methods in relation to those acquired from applying PSO and BFO methods. It should be mentioned that the values of PSO and BFO methods are obtained from [4]. These results are shown in Figs. (6-9). As observed in Fig. (6), the proposed method outperforms BFO and PSO. By applying QEA, oscillations are damped faster compared with other methods. The same phenomenon hold true in Figs. (7-9). Values of settling time are tabulated in Table 2, where, the value of settling time of generators 1 to 4 decrease to 6.1128 (sec), 6.9833 (sec), 3.8651 (sec) and 6.55 (sec), respectively, in comparison to PSO and BFO where it can be deduced that QEA is more accurate.

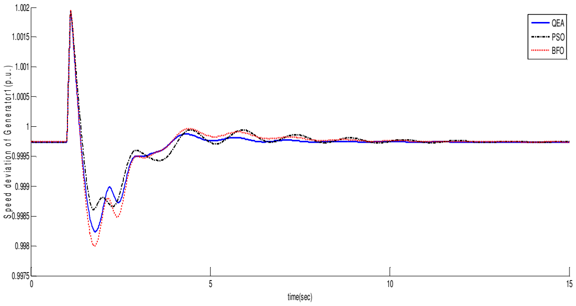

Fig. (6): Speed deviation of Generator1

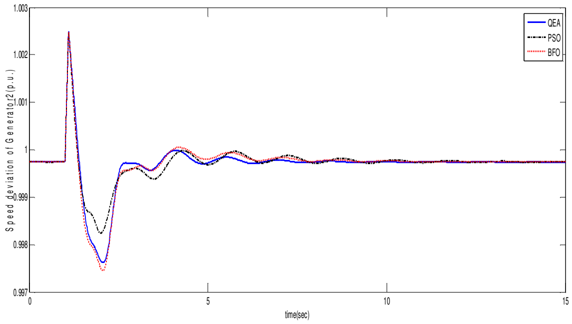

Fig. (7): Speed deviation of Generator 2

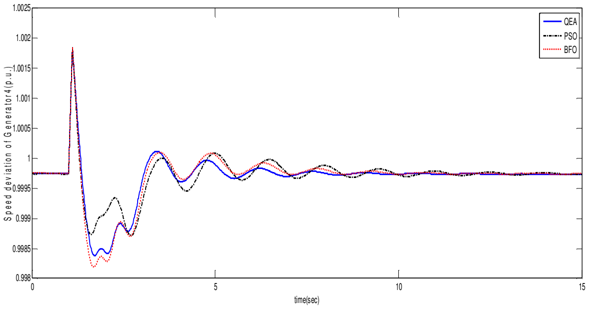

Fig. (8): Speed deviation of Generator 3

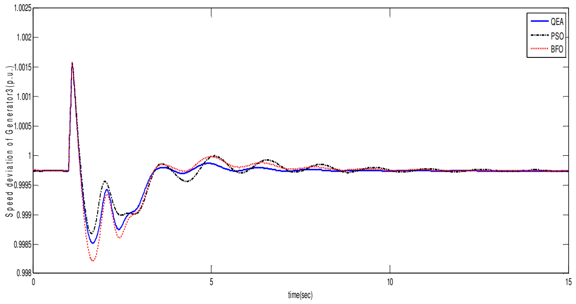

Fig. (9): Speed deviation of Generator 4

Table (2): The settling values for the 100 (m-sec) faults

Device	Algorithm		
	QEA	PSO	BFO
G1	6.1128	9.2833	7.6833
G2	6.9833	7.8667	6.7167
G3	3.8651	12.6	8.25
G4	6.55	10.6795	9.35

Here, the fault rate is increased by another 100 seconds. Better damping rate of first and third machines oscillations are observed in Figs. (10) and (11). The settling time values are tabulated in Table 3, at 6.33 (sec) and 6.3833 (sec) for the first and third generators, respectively, indicating that the proposed algorithm outperforms PSO and BFO. Moreover, according to Tables 4 and 5, the optimized parameters of four-machine system and ITAE criterion can be observed through the proposed algorithm.

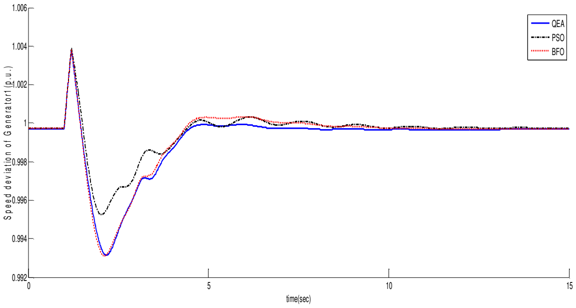

Fig. (10): Speed deviation of Generator 1

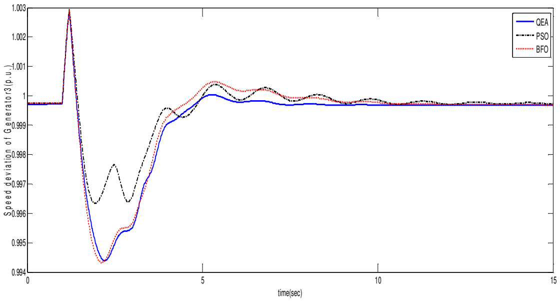

Fig. (11): Speed deviation of Generator 3

Table (3): The settling value for the 200 (m-sec) fault

Device	Algorithm		
	QEA	PSO	BFO
G1	6.33	8.6711	8.1
G3	6.3833	10.1579	8.5833

Table (4): ITAE criterion by QEA and PSO and BFO algorithms

Criterion	Algorithm		
ITAE	BFO	PSO	QEA
	0.0162	0.0251	0.0138

Table (5): Optimized parameters of four-machine system by QEA and PSO and BFO algorithms

Device	Parameter	Algorithm		
		QEA	PSO	BFO
G1	Ks	32.4336	15.36	48.07
	T1	0.4336	0	5.45
	T2	0.4336	0	7.61
	T3	0.4336	0	5.45
	T4	0.4336	0	7.61
G3	Ks	33.0117	21.22	51.19
	T1	1	3.95	6.96
	T2	1.0117	4.45	9.85
	T3	1	3.95	6.96
	T4	1.0117	4.45	9.85
SVC	Kp	1.4531	3.57	9.85
	Ki	433.4531	101.9	36.46

The values of terminal voltage for each 100 (m-sec) and 200 (m-sec) together with voltage change of first and second generators reference of 5% each are shown in Figs. (12-15).

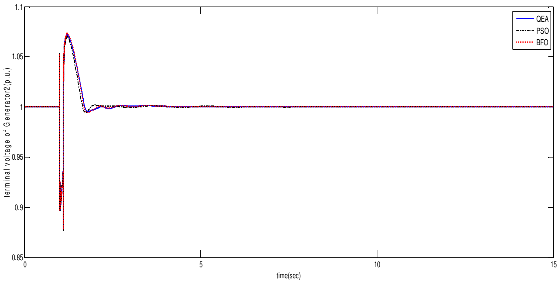

Fig. (12): The volatge terminal of machine (2) for 100 (m-sec) fualt

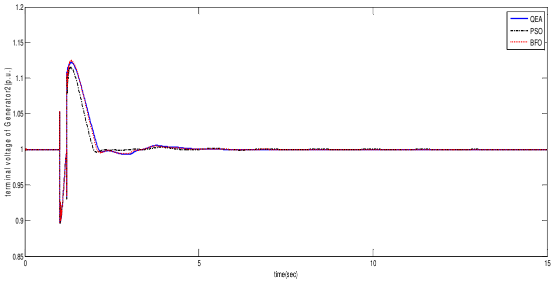

Fig. (13): The volatge terminal of machine (2) for 200 (m-sec) fualt

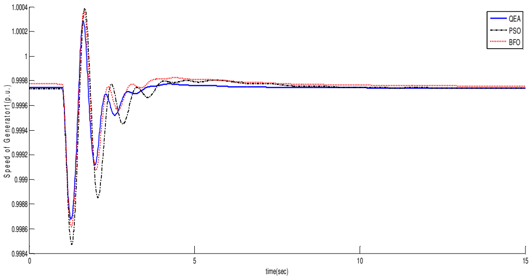

Fig. (14): Machine (1) speed at 5% reference voltage change

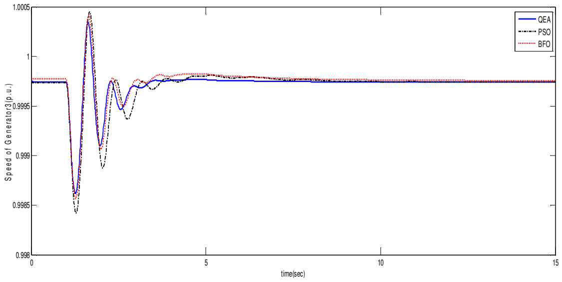

Fig. (15): Machine (3) speed at 5% reference voltage change

4.2. New England 39-Bus System

4.2.1. System Specifications

The second test system in this study is the New England 39-bus. This system is a simple display of the 345 KV from New England region with 39 busses, 46 lines and 10 generators placed in the buses 30 to 39. The first generator located in the 30th bus is the representative of a good number of generators. Further information on mentioned system, information related to the transmission lines and generation units and load are provided from [19]. The single line diagram of the mentioned system is illustrated in Fig. (16).

4.2.2. Proposed Scenarios of New England 39-Bus system

A three phase short circuit is designed with 100 (m-sec) to run simulations in this case. For this purpose, the simulation is run based on the following three scenarios:

- Scenario 1: A 100 (m-sec) three-phase fault at bus 4 at t=1 (sec) without SVC and PSS.
- Scenario 2: A 100 (m-sec) three-phase fault at bus 4 at t=1 (sec) uncoordinated PSS and SVC.

- Scenario 2: A 100 (m-sec) three-phase fault at bus 4 at t=1 (sec) coordinated PSS and SVC.

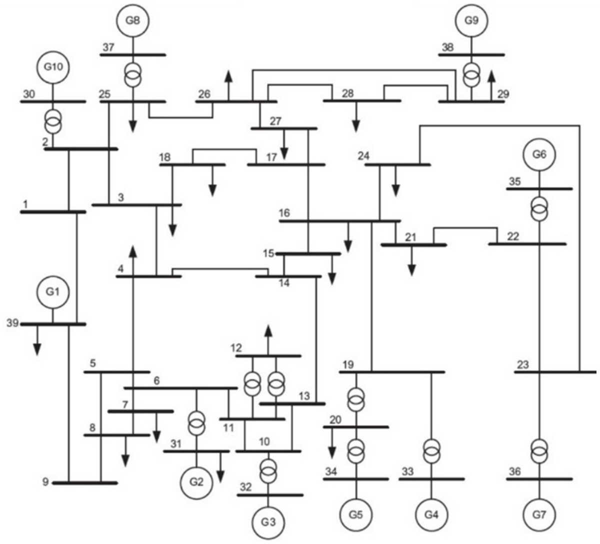

Fig. (16): New England 39-bus System [3]

4.2.3. Inilial arragments

To implement the mentonid scenarioes on the test system the PSAT toolbox is applied [19]. For this purpose, a time constant and gain are applied in SVC modeling [20] and the PSS model is expressed similar to the model presented in Fig. (2). Accordnigly, in addition to the PSS parameters, the gain K_r and time constant T_r parameters are added to improve optimization. The value of both the parameters are determind according to [3-4].

To reduce calculation operation, the parameters T2 and T4 are equal 0.1 and T1=T3 [19]. The SVC location is determined at bus 27, according to [21]. For optimization of PSSs localities of power system the variable state is defined. In case the variable state is 0, the PSS of the given generator exits the system and if variable state is 1, it would remain in optimization operation. Likewise, it the population generation pattern in the PSS optimizing algorithm is not allocated on any one of the generators, as a pre-assumption, PSS would be allocated on generators 5, 7 and 9 [22].

4.2.4. Assessing of New England 39-Bus system simulation results

Here, the operation of QEA for New England 39-bus in compersion with a system without PSS and SVC together with uncoordinated desing of PSS and SVC methods are assessed. The values of the parameters obtained through QEA are tabulated in Table 6. The changes in the following generatos' speed through QEA and a system without PSS and SVC together with uncoordinated desing of PSS and SVC methods are shown in Figs.(17-20):

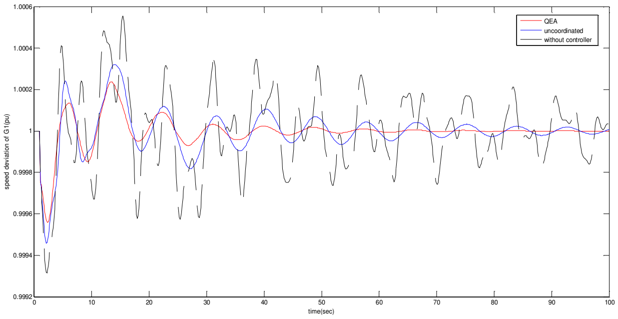

Fig. (17): Speed deviation of G1

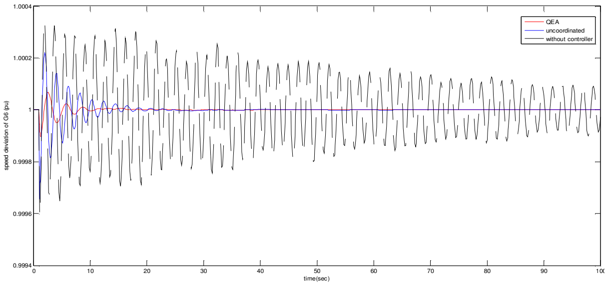

Fig. (18): Speed deviation of G6

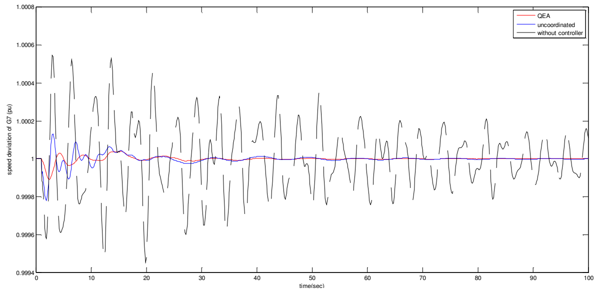

Fig. (19): Speed deviation of G7

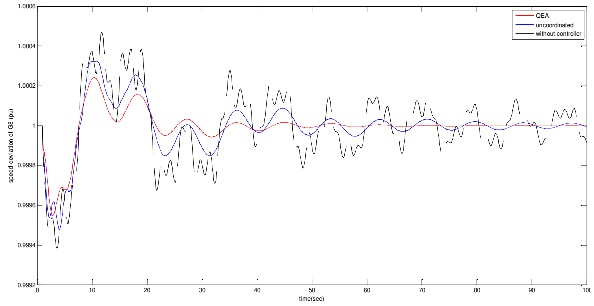

Fig. (20): Speed deviation of G8

According to Figs.(17-20), the generators' speed determined through QEA in relation to the other two states have less undershoot value. The settling time determind through QEA is at low value. Power system designed in coordination with PSS and SVC throgh QEA is more sustainable in operation in relation to other methods.

5. Conclusion

A coordinated design of power system stabilizer and SVC through the quantum-inspired evolutionary algorithm is proposed to increase power system stability. The results of stimulation run through the proposed algorithm is compared with those obtained from the coordinated designs of PSS and SVC through PSO and BFO algorithms. The results of this stimulation provide an increased power system stability in comparison with the available algorithms.

Table (6): Optimized PSS and SVC parameters of New England 39-Bus by QEA

Device	Parameter		
	K_{PSS}	T_1=T_3	State
G2	42.1875	0.1875	1
G3	200	0.3125	1
G4	166.1250	0.1250	0
G5	182.3125	0.3125	1
G6	24.3750	0.3750	0
G7	61	1	0
G8	5.3750	1	0
G9	178.4375	0.4375	1
G10	158.1875	0.1875	1
SVC	K_r	T_r	
	10	1	

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