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SIMULATION OF STATCOM FOR VOLTAGE QUALITY IMPROVEMENT IN POWER SYSTEM

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Abstract - Due to the reasons of economic, political and ecological character that appears in the construction of new transmission lines and also due to the increasing of the consumption request of the electric power, existing power transmission systems have some difficulties. One of the possible ways in order to solve these problems is to use the Flexible Alternate Current Transmission Systems (FACTS) devices. In this paper the application of STATCOM for voltage quality improvement in Azerbaijan power system was considered. Simulation was executed by using of MATLAB and Delphi software.

Keywords: Flexible AC Transmission Distributed Systems (FACTS), STATCOM, Voltage Flicker.

I. INTRODUCTION

Due to definition of IEEE/CIGRE the FACTS concept is based on the incorporation of power electronic devices and methods into the high-voltage side of the network, to make it electronically controllable. The concept of flexible AC transmission system consists in the realization of a system more performed through the control of the power flow and the rise of the transmission capability until the limits tolerated by the system.

The advantage of implementation of FACTS devices is to increase controllability and optimize the utilization of the existing power system capacities by replacing mechanical controllers by reliable and high-speed power electronic devices. It is known, that power flow is not directly controllable and for change the way power flows in the power system, we must change line impedance, voltage magnitude, or phase-difference angle.

The active and reactive power flow, along a transmission line connecting two buses is given by:

$$P_{12} = \frac{U_1 U_2}{X_L} \sin\delta \tag{1}$$

$$Q_{12} = \frac{U_1^2 - U_1 U_2 \cos\delta}{X_L} \tag{2}$$

where U_1 and U_2 are sending and receiving end voltage magnitudes, X_L is the impedance of the line and δ is the voltage phase angle difference. It can be seen from Equation (1) that the amount of the real power transmitted over the line can be increased by increasing the magnitude of the voltages at either end, reducing the line reactance, increasing the power angle. Flexible AC Transmission System (FACTS) increase transfer capability and provides control of one or more AC transmission system parameter.

The FACTS devices are based on the development of the power electronics such as thyristors and give the possibility to control one or more electrical parameters: voltage, current, and phase-difference angle [1, 2]. The basic applications of FACTS-devices are power flow control, increase of transmission capability, voltage control, reactive power compensation, stability improvement, power quality improvement, power conditioning, flicker mitigation, interconnection of renewable and distributed generation.

FACTS controllers divided into categories, which include series, shunt, combined series-series and combined series-shunt controllers. FACTS devices perform active impedance injection instead of inserting fixed impedance devices. Active impedance injection is a term used to describe either compensation achieved by injecting an AC voltage which is accomplished using a synchronous voltage source (SVS) which generates sinusoidal voltages at the fundamental frequency and has controllable amplitude and phase angle.

The SVS is capable of generating or absorbing reactive power by controlling the injected voltage magnitude. There are two groups of FACTS devices for solve transmission problems in power system. The first group employs reactive impedances or tap-changing transformers with thyristor switches as controlled elements. The Static Synchronous Compensator (STATCOM), Thyristor Controlled Series Capacitor and Phase Shifter, belong to this group of FACTS controllers. The second group employs voltage-sourced switching converters: Static Synchronous Compensators, Static Synchronous Series Compensators, Unified Power Flow Controllers and Interline Power Flow Controllers [1, 2, 5-7].

Shunt FACTS devices such as the static VAR compensator and static synchronous compensator are typically used for reactive VAR compensation and voltage support. Series devices such as the thyristor controlled series capacitor and the static synchronous series compensator can be used for active power flow controlling on transmission lines. Series-shunt devices such as the universal power flow controller can be used for realization both functions. The benefits of power flow control are relieving overloaded lines, reduce transmission losses, maintain acceptable voltages, and improve stability, full utilization of existing system. Cost, size and installation are the limitations of this problem

II. STATIC SYNCHRONOUS COMPENSATOR

The shunt controllers may be variable impedance, variable source or a combination of them. Shunt controllers, such as Static Var Compensator (SVC) inject current into the system at the point where they are connected. If the injected current is in phase with the line voltage, the controller adjusts reactive power. If the current is not in phase with the line voltage, the controller adjusts active power.

Other shunt controller named the static synchronous compensator is based on a solid-state voltage source, implemented with an inverter and connected in shunt to the power system through a coupling reactor, generating balanced set of three sinusoidal voltages at the fundamental frequency, with controllable amplitude and phase angle. The Statcom is based on voltage sourced converter (VSC), has no inertia and no overload capability [3-5]. A schematic representation of the STATCOM and its equivalent circuit are shown in Figure 1.

Computation and control of power flow for power systems embedded with STATCOM appear to be fundamental for power system analysis and planning purposes. STATCOM can supply the capacitive and the inductive compensation and is able to independently control its output current over the rated maximum irrespective of the amount of ac system voltage. Thus, the STATCOM can provide full capacitive-reactive power at any system voltage and STATCOM output voltage can be regulated such that the reactive power of the STATCOM can be changed.

Among all control options, control of the voltage of the local bus, which the STATCOM is connected to, is the most-recognized control function. Note that the other control possibilities have not fully been investigated in power flow analysis [8]. The STATCOM equivalent circuit shown in Figure 1 is used to derive the mathematical model of controller for inclusion in power flow algorithms.

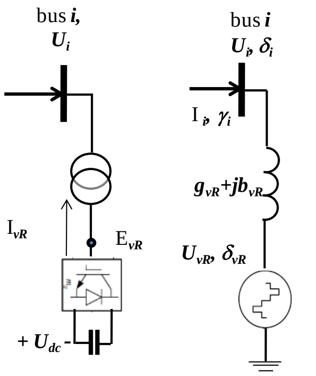

Figure 1. A schematic representation of the STATCOM and its equivalent circuit

The power flow equations for the STATCOM are derived below from assuming the following voltage source representation [1-2]:

$$E_{vR} = U_{vR}(\cos\delta_{vR} + j\sin\delta_{vR}) \quad (3)$$

where U_{vR}, and δ_{vR} is the VSC output voltage and phase angle.

According to the single line and phasor diagram in Figure 1, the power flow constraints of the STATCOM are:

$$P_{vR} = U_i^2 g_{vR} - U_i U_{vR}(g_{vR}\cos(\delta_i - \delta_{vR}) + \\ + b_{vR}\sin(\delta_i - \delta_{vR})) \quad (4)$$

$$Q_{vR} = -U_i^2 g_{vR} - U_i U_{vR}(g_{vR}\sin(\delta_i - \delta_{vR}) - \\ - b_{vR}\cos(\delta_i - \delta_{vR})) \quad (5)$$

where g_{vR} and b_{vR} is the VSC conductance and susceptance respectively. Note that the active power flow between the AC source and the VSC is controlled by the phase angle δ_{vR}, and the reactive power flow is determined mainly by the magnitude of the voltage source, and the VSC output fundamental voltage, U_{vR}.

III. FLICKER

Power quality concept describes the quality of the supplier voltage in relation to the transient breaks, falling voltage, harmonics and voltage flicker. Voltage fluctuations are systematic variations of the voltage envelope or a series of random voltage changes, the magnitude of which does not normally exceed the voltage ranges of 0.9 to 1.1 pu.

The term flicker is derived from the impact of the voltage fluctuation on lamps such that they are perceived by the human eye to flicker. Technically, voltage fluctuation is an electromagnetic phenomenon while flicker is an undesirable result of the voltage fluctuation in some loads.

Voltage flicker is caused by an arc furnace, one of the most common causes of voltage fluctuations on utility transmission and distribution systems [9, 10]. Voltage flicker on lighting and on television apparatus must be limited to avoid disturbances to human eyes (e.g., for voltage variations greater than approximately 1.5% at a frequency of 10 Hz).

The disturbance becomes perceptible for voltage variation frequency of 10 Hz and relative magnitude of 0.26%. IEC 61000-4-15 defines the methodology and specifications of instrumentation for measuring flicker. This standard devises a simple means of describing the potential for visible light flicker through voltage measurements. The measurement method simulates the lamp/eye brain transfer function and produces a fundamental metric called short-term flicker sensation (P_{st}).

This value is normalized to 1.0 to represent the level of voltage fluctuations sufficient to cause noticeable flicker to 50 percent of a sample observing group. Another measure called long-term flicker sensation (P_{lt}) is often used for the purpose of verifying compliance with compatibility levels established by standards bodies and used in utility power contracts. This value is a longer-term average of P_{st} samples [11].

The flicker signal is defined by its rms magnitude expressed as a percent of the fundamental. The relative voltage drop is expressed by Equation (6):

$$\frac{\Delta U}{U_n} = \frac{R \cdot \Delta P + X \cdot \Delta Q}{U_n^2} \quad (6)$$

where ΔP and ΔQ are the changes in active and reactive power; U_n is the nominal voltage; and R and X are resistance and reactance. Since R is usually very small in comparison to X, ΔU is proportional to Q (reactive power). Therefore, voltage flicker depends on reactive power control.

Voltage flicker is the power quality problems which are introduced to the power system as a result of nonlinear behavior of the arc furnace operation. For analyze flicker generated by an arc furnace, accurate arc furnace models are necessary, because an AC arc furnace is an unbalanced, nonlinear and varying load. An arc furnace load may cause many other problems to the power system quality, such as harmonics, inter-harmonics.

In [12] analyzed the voltage flicker mitigation using PWM-Based Distribution STATCOM, where the author concluded that the concept of power quality describes the quality of the supplier voltage in relation to the transient breaks, falling voltage, harmonics and voltage flicker.

In [13] authors have analyzed about the static shunt compensation for voltage flicker reduction and power factor correction using STATCOM. Notice also that, the active filters are used for the voltage flickers mitigation as well.

In Table 1 values of flicker short term of the electro arc furnace in Baku Steel Company on 05.04.201, measured by Simeas-Q device are presented.

Table 1. Values of flicker short term

Flicker short term (05.04.2011)			
Time	*L1*	*L2*	*L3*
15:50:00	1.159348	0.992556	0.953788
16:00:00	0.809954	0.788722	0.81451
16:10:00	0.991494	1.01304	0.810185
16:20:00	0.955247	0.915276	0.737868
16:30:00	1.03554	0.856671	0.833911
16:40:00	0.027642	0.060892	0.099342
16:50:00	0.041777	0.038365	0.071195
17:00:00	7.52362	8.409815	8.647245
17:10:00	5.232827	5.372955	6.182413
17:20:00	4.39148	3.56262	4.357201

In Figure 2 changes of short-time flicker of the electro arc furnace in Baku Steel Company on 05.04.2011 are shown. Due to the achievements in the semiconductors, FACTS devices have been gradually noticed to be used for voltage flicker compensation.

The FACTS devices such as SVC, STATCOM, and UPFC have been able to solve the voltage flicker problems by rapidly controlling the reactive power.

The mitigating devices such as STATCOM are the most frequently used devices for reduction in the voltage flicker. SVC devices because of their complicated control algorithms have some problems such as injecting a large amount of current harmonics to the system and causing spikes in voltage wave forms.

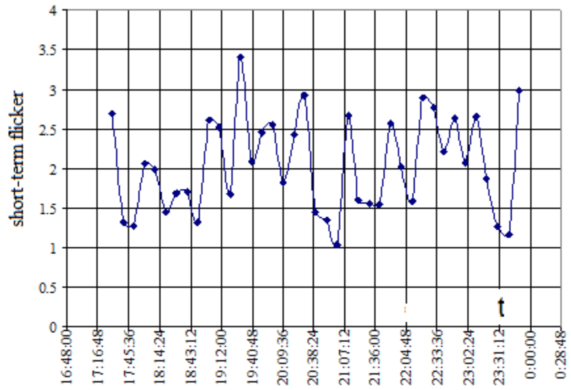

Figure 2. Changes of short-time flicker electro arc furnace

IV. SIMULATION MODEL FOR FLICKER ANALYSIS

A MATLAB based program was developed for the flicker analysis of electrical power systems. Simulation model for flicker analysis in electrical power systems, shown in Figure 2. Model parameters, including parameters of a power supply system and arc furnace are presented in Table 2.

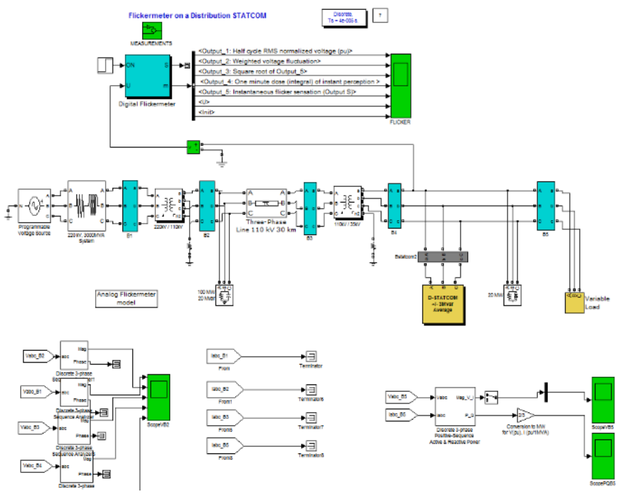

Figure 2. MATLAB simulation model for flicker analysis

Table 2. System and arc furnace model parameters

No	Model element	Parameters
1	Power system	Resistance R = 12.1 Ohms Inductance L = 0.3852 H
2	Three-phase transformer 220/110 kV	Nominal power P_{nom} = 400 MVA
3	Three-phase transmission line 110 kV	Line length = 30 km
4	Three-phase transformer 220/110 kV	Nominal power P_{nom} = 400 MVA
5	STATCOM	35kV, +/- 15 Mvar
6	Constant load	P=2 MW
7	Variable Load	Nominal load I = 500 Arms Power factor = 0.9 Modulation amplitude = 300 Arms, Frequency = 5 Hz

The STATCOM regulates bus B4 voltage by absorbing or generating reactive power. This reactive power transfer is done through the leakage reactance of the coupling transformer by generating a secondary voltage in phase with the primary voltage. This voltage is provided by a voltage-sourced inverter.

When the secondary voltage is lower than the bus voltage, the STATCOM acts like an inductance absorbing reactive power. When the secondary voltage is higher than the bus voltage, the STATCOM acts like a capacitor generating reactive power.

The STATCOM consists of the following devices:

1. Coupling transformer which ensures coupling between the PWM inverter and the network.
2. A voltage-sourced PWM inverter, which is replaced on the AC side with three equivalent voltage sources. Harmonics generated by the inverter are therefore not visible with this average model. On the DC side, the inverter is modeled by a current source charging the DC capacitor.

The DC current I_{dc} is computed so that the instantaneous power at the AC inputs of the inverter remains equal the instantaneous power at the DC output

3. LC damped filters connected at the inverter output. Resistances connected in series with capacitors provide a quality factor of 40 at 60 Hz.
4. Capacitor acting as a DC voltage source for the inverter
5. A voltage regulator that controls voltage at bus B4
6. Anti-aliasing filters used for voltage and current acquisition.

A flicker meter device is used to measure the instantaneous flicker sensation on terminal voltage of a Statcom unit. Flicker meter block is a digital implementation (discrete model) of the flicker meter described in the IEC 61000-4-15 standard.

The input of this device is the phase voltage that will be analyzed after the flicker meter. Output is the instantaneous flicker sensation. Detailed description of the standard block diagram is resulted in [12]. Figure 3 shows voltage magnitude in point where Statcom connected.

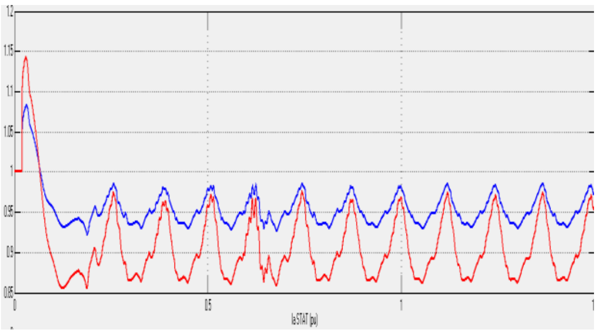

Figure 3. Representation of voltage magnitude

The variable load current magnitude is modulated at a frequency of 5 Hz. This load variation allowed observes the ability of the Statcom to mitigate voltage flicker. In Figure 4 half cycle RMS normalized voltage (pu) and harmonics are s shown.

Note that Statcom operated in mode voltage regulation and reactive power regulation. This model is suited for observing harmonics and control system dynamic performance over relatively short periods of times (hundreds of milliseconds to one second).

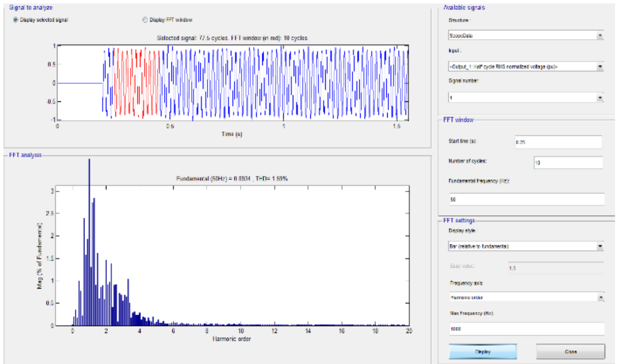

Figure 4. Half cycle RMS normalized voltage and harmonics

V. MODELLING RESULTS FOR AZERBAIJAN POWER SYSTEM

The seven-bus equivalent scheme 220-330-500 кV of Azerbaijan power system (Figure 5) is used to include one STATCOM connected at bus 6, to maintain the nodal voltage magnitude at 220 kV. For calculation was used power flow software developed by the authors at the Azerbaijan Research Institute of Energetic and Energy Design. Table 3 shows the input bus data for seven-bus test network. The input branch data for above test network has shown in Tables 4 and 5. Voltage magnitudes and phase angles for equivalent scheme 220-330-500 kV are given in Table 6.

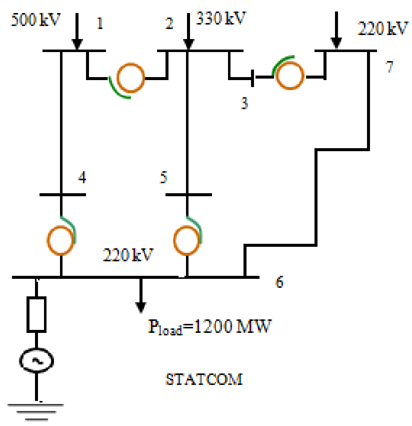

Figure 5. Seven-bus equivalent scheme 220-330-500 kV

Table 3. Bus data information

No	U kV	P_l MW	Q_l MVAr	P_g MW	Q_g MVAr	Q_{min} MVAr	Q_{max} MVAr
1	505	0	0	800	0	0	0
2	330	0	0	500	0	0	0
3	330	0	0	0	0	0	0
4	505	0	0	0	0	0	0
5	330	0	0	0	0	0	0
6	220	1200	0	0	0	-500	800
7	220	0	0	0	0	0	0

Table 4. Branch data (line) information

From	To	*r*	*x*	*b*	*g*
1	4	7.25	77	-900	0
2	3	0.14	1.53	-17.04	0
2	5	7.03	74.69	-873	0
7	6	10.4	50.4	-1200	0

Table 5. Branch data (transformer) information

From	To	*r*	*x*	*b*	*g*
3	7	0.5	23	20.31	4.2
1	2	0.4	22.5	12.4	2
5	6	0.5	23.6	6.38	1.22
4	6	0.6	35.1	10.24	1.92

Table 6. Voltage magnitudes and phase angles for equivalent scheme

Buses	Magnitudes kV	Angle degree
1	510.00	0
2	337.00	-1.67
3	336.94	-1.87
4	498.17	-14.01
5	329.52	-16.00
6	220.00	-20.41
7	225.22	-4.93

As can be seen from Table 6, the use of STATCOM at node 6 leads to an improvement of voltage levels in power flow and loss reduction results for bus 6 are given in Table 7.

Table 7. Loss reduction results for test network

No	P_6 MW	U_6 kV	Q_6 MVAr	ΔP MW	Loss reduction MW
1	800	220	-96.17	15.69	4.43
		200	-393.34	20.12	
2	1000	220	-31.66	33.18	4.76
		200	-311.50	28.42	
3	1200	220	44.87	33.63	5.58
		200	-229.68	39.21	
4	1400	220	139.1	45.71	6.86
		200	-156	52.57	
5	1600	220	-248.97	61.76	8.69
		200	16.30	70.45	

Power flow results showed that the installation of STATCOM at node 6 leads to a reduction of losses up to 4.43-8.86 MW. For optimum modes active power flow increases on high-voltage lines 330 and 500 kV and decreases on lines 220 kV. At the rate of energy losses costs equal cost of electric power realization (0.041 manat/kW*hour), we receive economic profit of $\Delta C = 8.6\times10^6 \times 4.1\times10^{-2} = 35.26\times10^4$ Manat.

VI. CONCLUSION

1. Voltage flicker is caused by an arc furnace, one of the most common causes of voltage fluctuations on utility transmission and distribution systems
2. The analysis and simulation of a STATCOM application for the mitigation of voltage flicker problems are presented.
3. A MATLAB based program was developed for the flicker analysis of electrical power systems. The presented simulation model represents a useful tool in energy management system. The received results show that STATCOM can reduce the voltage flicker caused by nonlinear loadings such as electro arc furnaces.
4. Computer modelling of power flow on an example 7 buses equivalent scheme of Azerbaijan power system for voltage management by using STATCOM executed.
5. Power flow results showed that the installation of STATCOM at node 6 leads to a reduction of losses up to 8 MW.

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BIOGRAPHIES

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