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Voltage Fluctutaion Compensation Due to Induction Motor Starting in Distribution System Using Fuzzy-Based Control of Unified Series Shunt Compensator

[1]M. Mohammadi, [2]S. Bahmanyar, [3]H. Saremi

[1,2,3]*Department of Electrical Engineering, College of Engineering, Borujerd Branch, Islamic Azad University, Borujerd, Iran.*

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ABSTRACT

Voltage flicker is caused by loads that exhibit continuous, rapid variations in load current. With the increase in the number of loads and the increase in the power consumed, therefore, it grew rapidly. Induction motors and its starting under distribution network is the main generator of voltage flicker which affects the performance of other sensitive loads. Custom power devices have been gradually noticed to be used for voltage flicker mitigation. Unified series shunt compensator (USSC) has been widely used to mitigate various power quality disturbances in distribution network. USSC, it is possible to compensate a variety of power quality problem much better than DSTATCOM, DVR and other custom power device. Hence due to multi capability of USSC in power quality improvement, this paper presents the scheme based on fuzzy bang-bang control for USSC. Using Fuzzy Logic Control (FLC) based on bang-bang control; the USSC will contribute to the mitigation of flicker without deteriorating the effect of the other compensating devices.

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INTRODUCTION

The relationship between power quality and distribution system has been a subject of interest for several years. Recently, with the growth of industry manufacturers and population, electric power quality becomes more and more important. As one of the most common power quality issues, flicker, causing from feeder voltage fluctuation, influences domestic lighting and sensitive apparatus of nearby transmission and distribution system. The disturbance becomes perceptible for voltage variation frequency of 10 Hz and relative magnitude of 0.26% [1-2]. Huge non-linear industrial loads such as the electrical arc furnaces, pumps, welding machines, rolling mills and others are known as flicker generators [3-4]. Water pump implemented in agriculture sectors due to employ the induction motors is one of the main flicker source in distribution system. Many studies have been focused on flicker mitigation. In [5] evaluation of cascade-multilevel converter based STATCOM for arc furnace flicker mitigation through a TNA system is presented and discussed. Also in [6] the mitigation of voltage flicker and reduction in THD by using STATCOM has been investigated. In [7-8] the authors present a new approach for the dynamic compensation of flicker and harmonics in arc furnace power systems based on the UPFC. In [9] suppression of voltage flicker by saturable reactor operating under forced magnetization is investigated. Authors describe a possibility of improving the power quality in AC EAF networks by help of a forced magnetized saturable reactor in series with the abruptly variable load. The advantage of the forced magnetization is an instant intervention in variations of the load current due to the physical behavior of the saturable reactor in contrast to thyristor-controlled reactors, which have response time delays [10]. In [11] distribution series capacitor application for improved motor start and flicker mitigation is analyzed. In [12-13] the paper is concerned with a pre-flicker compensation strategy adopted by a dynamic voltage restorer (DVR) to mitigate voltage flicker in a power system. The presented DVR configuration based on flying capacitor multicell (FCM) converter is proposed to mitigate the voltage flicker because of taking the FCM converter advantages such as transformer-less operation and natural self-balancing of flying capacitors voltages. The proposed DVR consists of a series converter on the source-side and a shunt rectifier on the load-side. In [14] the SVC for mitigation of flicker from electric arc furnaces is presented and discussed.

Corresponding Author: M. Mohammadi, Department of Electrical Engineering, College of Engineering, Borujerd Branch, Islamic Azad University, Borujerd, Iran

The proposed devices in [1-14] often used in MV level of power system for voltage flicker mitigation due to arc furnace. On the other hand one the main flicker source in distribution system is starting the induction motors. Some of custom power devices that employed in distribution system to improve power quality are DVR, STATCOM, SVC and USSC. Many investigations show that USSC is able to mitigate many types of power quality disturbances. So this paper addressed the voltage flicker mitigation due to starting induction motors in distribution system. USSC has two converters, series converter and shunt converter. This facility let this device to improve power quality quickly and effectively. In this paper, the control strategy and performance of the USSC for flicker mitigation at distribution level is presented and evaluated through a Fuzzy Bang-Bang Control (FBBC).

Flicker concepts:

Flicker is a power system disturbance, which can be defined as the visual perception of variations in luminance of lighting equipment. These variations are caused by the fluctuations in the supply voltage. For voltage deviations the change is usually expressed as $\Delta V / V$. The fluctuations are characterized by the magnitude of the voltage changes and the frequency with which they occur. The human visual system reacts differently to light with reference to its frequency of voltage deviations. Flicker gives rise to visual discomfort and can lead to complaints from the customer to the utility. Flicker is evaluated in terms of a P_{ST} (Short Term Flicker Severity). The threshold at which flicker becomes perceptible to the human eye is at a PSI =1. The human eye is particularly sensitive to the variations in luminance in lighting equipment, in the region of 8 - 10Hz. [15].

The voltage fluctuations are caused by the fluctuating load current drawn by variable loads, and the supply impedance of the power system, as illustrated by Figure 1. Variable loads include loads such as crushers, arc furnaces and sawmills, induction motors [16].

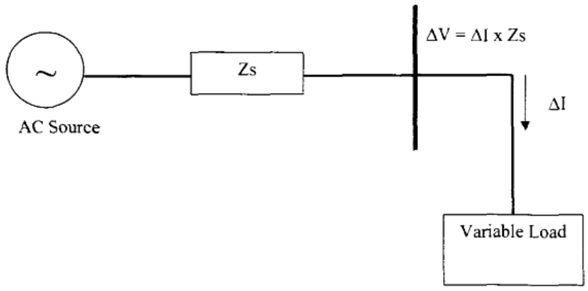

Fig. 1: Voltage Fluctuation Caused by Variable Load

The rapid expansion of power systems and the vast usage of modern load types have caused the area of power quality to become a major issue from an obscurity within few years. Amongst many power quality problems voltage flicker has gained a growing concern from utilities, especially in the areas of transmission and distribution planning. Voltage flicker is a common term used to describe systematic fluctuations in the voltage envelope or a series of random voltage changes that can cause perceptible variations in the illumination of lighting devices. The perceptibility of light flicker depends upon the magnitude and the frequency of the variation.

The most basic flicker phenomenon can be explained by amplitude modulating the ac voltage waveform by a sine wave seen as the envelope of the waveform, as shown in Figure 2 [17].

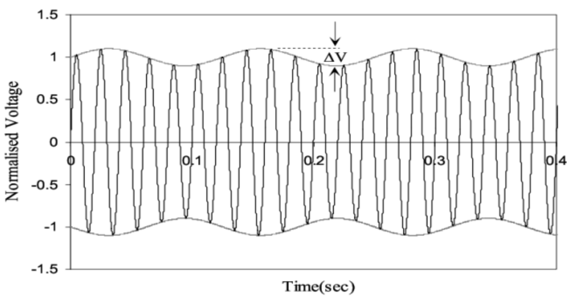

Fig. 2: Typical flicker voltage waveform

USSC modeling:

The Unified Series Shunt Compensator is a combination of series and shunt voltage source inverters as shown in Figure 3. The basic components of the USSC are two 12-pulse voltage source inverters composed of forced commutated power semiconductor switches, typically GTO thyristor valves. One voltage source inverter is connected in series with the line through a set of series injection transformers, while the other is connected in shunt with the line through a set of shunt transformers. The dc terminals of the two inverters are connected together and their common dc voltage is supported by a capacitor bank [18]. The USSC is almost similar to the UPFC, but the only differences are that the UPFC inverters are in shunt series connection and used in transmission systems whereas the USSC inverters are in series-shunt connection and used in distribution systems [19].

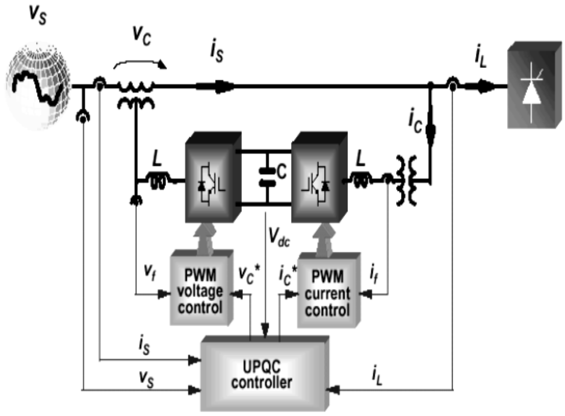

Fig. 3: General Scheme of USSC

Capabilities of USSC versus DSTATCOM and DVR:

Since the introduction of FACTS and custom power concept [20], devices such as unified power-flow controller (UPFC), synchronous static compensator (STATCOM), dynamic voltage restorer (DVR), solid-state transfer switch, and solid-state fault current limiter are developed for improving power quality and reliability of a system [21], [22]. Advanced control and improved semiconductor switching of these devices have achieved a new era for power-quality mitigation. Investigations have been carried out to study the effectiveness of these devices in power-quality mitigation such as sag compensation, harmonics elimination, unbalance compensation, reactive power compensation, power-flow control, power factor correction and flicker reduction [23-24]. These devices have been developed for mitigating specified power-quality problems. By using a unified approach of series-shunt compensators it is possible to compensate for a variety of power-quality problems in a distribution system including sag compensation, flicker reduction, unbalance voltage mitigation, and power-flow control [25]. Usually individual custom power devices such as DSTATCOM and DVR focus on solving specific power quality problems in a distribution system. However, by using USSC, it is possible to compensate a different power quality problem as compared to DSTATCOM and DVR as indicated in Table 1 [26].

Table 1: Power quality mitigation using USSC versus others custom power devices

Power Quality Mitigation	DVR	D-STATCOM	USSC
Sag Compensation	YES	Limited	YES
Voltage Flicker	NO	YES	YES
Unbalance	NO	YES	YES
UPS Mode	YES	YES	YES
Power Flow Control	NO	NO	YES
Harmonic Elimination	NO	YES	YES

It is noted that, mitigated load voltage by the DVR is a steady state value but this value is lower than mitigated value obtained by USSC. In other words the USSC can mitigate voltage sag better in compared to DVR and D-STATCOM. Also in case of voltage flicker, unbalance and harmonics elimination it is much effective. Similarly, D-STATCOM is unable to control power flow. It is seen that the proposed USSC can mitigate variety of PQ problems [27].

USSC installation in distribution system:

Before modeling the USSC, all distribution system components, i.e., lines and cables, loads, transformers, large motors and generators have to be converted into equivalent reactance ($\boldsymbol{X}$) and resistance ($\boldsymbol{R}$) on common bases. The main system component models are used in the formulation of impedance matrix for voltage sag calculation [28]. In steady state analysis, the series and shunt inverters of the USSC are presented by two voltage sources $\boldsymbol{V}_{dq}$ and $\boldsymbol{V}_{sh}$ respectively as shown in Figure 4.

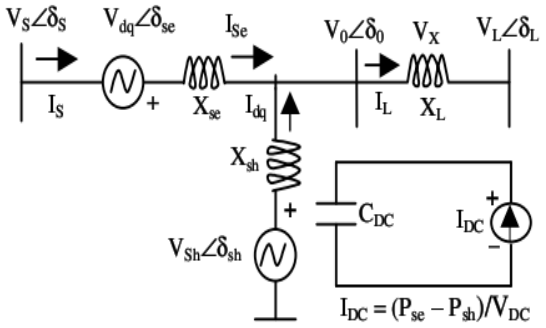

Fig. 4: Equivalent circuit of USSC

X_{sc} and X_{sh} represents the reactance of the transformers associated with the series and shunt voltage source inverters, respectively. Therefore, voltage equation of series and shunt inverters can be expressed as follows:

$$V_s = -V_{dq} + I_{se}(jX_{se}) + V_0 \tag{1}$$

$$V_s + V_{dq} - I_{se}(jX_{se}) = V_{sh} + I_{dq}(X_{sh}) \tag{2}$$

$$I_s = I_{se} = I_{dq} + I_L = \frac{V_{sh} - V_0}{X_{sh}} + I_L \tag{3}$$

$$I_s = I_{se} = I_{dq} + I_L = \frac{V_{sh} - V_0}{X_{sh}} + I_L$$

Where I_{sc} and I_{dq} are the series and shunt inverter currents, respectively.

The voltage across the distribution line reactance, X_L is

$$V_X = V_s + V_{dq} - I_{se}(jX_{se}) - V_L = V_0 - V_L = X_L.I_L \tag{4}$$

Where, I_L is distribution line current.

The voltage, V_X, across the distribution line can be changed by changing the inserted voltage, V_{dq}, which is in series with the distribution line. If we consider V_{dq}=0, the distribution line sending end voltage, V_S, leads the load voltage by an angle δ i.e $\delta_S - \delta_L$.

The resulting real and reactive power flows at the load side are P and Q, which are given as follows:

$$P_{ussc} = \frac{V_0.V_L}{X_L}\sin\delta \tag{5}$$

$$Q = \frac{V_0.V_L}{X_L}(1-\cos\delta) \tag{6}$$

With an injection of V_{dq}, the distribution line voltage V_0 will lead the load voltage V_L, and $\delta_0 > \delta_L$., thus the resulting line current and amount of flow Will be changed. With a larger amount of V_{dq} injection, V_0 now lags the load voltage V_L, and $\delta_0 < \delta_L$.

Consequently, the line current and power flow will be reversed.

Control strategy of series inverter:

Series converter provides the main function the USSC by injecting a voltage Vdq with controllable magnitude ***Vdq*** and phase angle δ_{se} in series with the line via an insertion transformer. This injected voltage acts essentially as a synchronous ac voltage source. The feeder current flows through this voltage source resulting in reactive and real power exchange between it and its ac system. The reactive power exchanged at the ac terminal (ie. at the terminal of series injection transformer) is generated internally by the converter. The real power exchanged at the ac terminal is converted into dc power, which appears at the dc link as a positive or negative real power demand.

According to the theoretical concepts, the rotation of series voltage phasor ***Vdq*** with angle δ_{se} cause variation of both the transmitted real power 'P' and the reactive power 'Q' with δ_{se} in a sinusoidal manner. For validating the proposed circuit model of USSC, the magnitude of series injected voltage is kept constant at 2KV and its angle is varied from 0^o to 360^o. The variation in real and reactive power is investigated and it is observed that the variation of real and reactive power is sinusoidal with variation in angle, thus coinciding with theoretical concepts. It can be seen that the transmitted real power is maximum at angle 90^o, minimum at angle 270^o and medium at angle 0^o. Hence, these values are selected in the switching function. The target of damping control is to conduct proper switching of C0, C1 or C2 at strategic times as to quickly mitigate voltage flicker. The output of series converter can be bang-bang controlled to three different values:

$$\text{Vdq} = \begin{cases} |V|\angle 0 \ \ \textit{When switch C0 is closed.} \\ |V|\angle 90 \ \ \textit{When switch C1 is closed.} \\ |V|\angle 270 \ \ \textit{When switch C2 is closed.} \end{cases} \tag{7}$$

Where Vdq is the voltage injected by the USSC; is the maximum magnitude of voltage that can be injected by the USSC.

The ultimate objective of this work is to implement fuzzy logic controller at the line in which USSC is connected. Fuzzy logic controller is an intelligent technique which has been implanted in the control of facts devices on power system. Mridul Jha. and S.P. Dubey in [29] investigated the Neuro-Fuzzy based controller for a three phase four wire shunt active power filter . Also some authors have utilized the fuzzy approach in the control of renewable energies. By [30] the implementation of fuzzy logic controller in photovoltaic power generation using boost converter and boost inverter has been analyzed. The inputs to fuzzy logic controller are V and δ measured at USSC terminals. For the output, the fuzzy logic controller will choose one of the three switch states from C0, C1 and C2 through competition. A simple fuzzy logic scheme comprises three functioning blocks, namely fuzzification, implication and inference, and selection of control. Input data are processed through these three blocks sequentially.

Fuzzification:

Crisp input data need to be converted into membership grades to which they belong to each of the associated linguistic levels. These levels are represented by fuzzy sets. Fuzzification serves as data preprocessor for implications of linguistic rules in a later stage. There are 10 distinct linguistic levels, namely $A_{1\text{-}10}$, for input V and 5 distinct linguistic levels, namely $B_{1\text{-}5}$, for δ. Membership functions for the corresponding fuzzy sets are distinct and triangular. A heuristic trial-and-error procedure is needed to find the appropriate fuzzy partitioning by comparing the present and desired response for fuzzy logic control.

Implication and inferencing:

Various fuzzified inputs are fed into a fuzzy rule base for implication and inferencing. Linguistic control rules are constructed based on observations of dynamic behaviors and switching curves.

With the use of two state inputs (V and δ), we obtain a two-dimensional rule base with 10 x 5 linguistic levels as in Table 2. The rule base is a collection of fuzzy conditional statements in the form of 'if-then' rules. Each rule carries a weight α_i (called firing strength), which is a measure of the contribution of ***i^th^*** rule to the overall fuzzy control action. The firing strength α_i is defined as:

$$\alpha_i = \mu_A(x_0)\Lambda\mu_V(y_0) \tag{8}$$

Where $A \in V, B \in \delta$ ***A***; ***μ*** denotes grade of membership defined for input state (V and δ), ***xo*** and ***yo*** are the input variables used at a particular time instant; and ***Λ*** is the fuzzy 'AND' operator.

Table 2: Two-dimensional fuzzy control rules

δ	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
B_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1
B_2	C_1	C_1	C_1	C_1	C_2	C_1	C_1	C_1	C_1	C_1
B_3	C_1	C_1	C_1	C_2	C_2	C_2	C_1	C_1	C_1	C_1
B_4	C_1	C_1	C_2	C_2	C_2	C_2	C_0	C_0	C_1	C_1
B_5	C_2	C_2	C_2	C_2	C_2	C_2	C_0	C_0	C_1	C_1

The membership value of each possible switching state C0, C1 and C2 for the FLC is obtained as:

$$\mu_i(C_0) = \frac{\sum \alpha_i}{4} \quad i = 40,41,50,51 \tag{9}$$

$$\mu_i(C_1) = \frac{\sum \alpha_i}{32} \quad i = 1,2,3,... \tag{10}$$

$$\mu_i(C2) = \frac{\sum \alpha_i}{14} \quad i = 15,24,25,26,... \tag{11}$$

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The main purpose of selection of control is to choose a non-fuzzy discrete control that best responds to current system oscillations. The final discrete FLC output indicates the final switching state chosen from C0, C1 and C2. The choice is competitive and only one switching state with highest membership μi among C0, C1 and C2 is chosen.

Simulation and result:

The single line diagram of the network in which field measurements were carried out is shown in Figure 5.

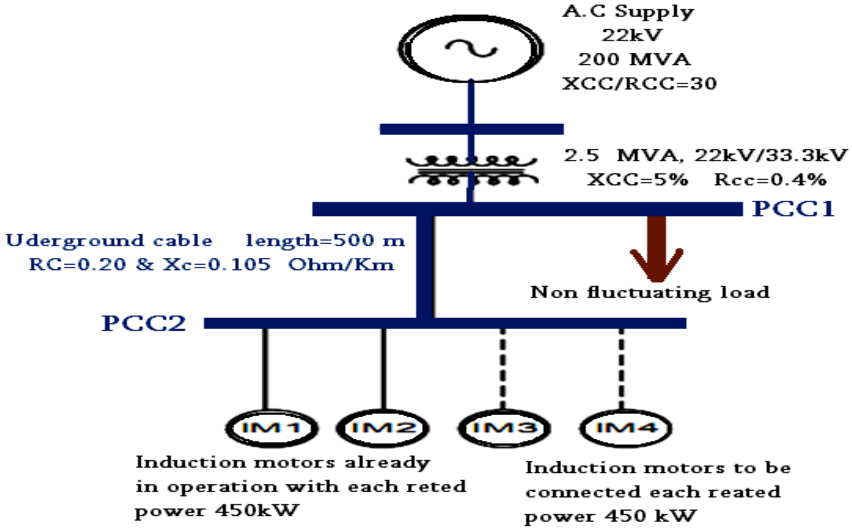

Fig. 5: Test power system considered for flicker mitigation using USSC

The transformer (3.3/22 kV/kV) has a rated apparent power of 2.5MVA.The cable connection between water pumping station and the transformer is approximately 500 m long. The cable impedance is 0.120+j0.015 $\Omega/\text{km}/\text{phase}$ according to available network data. The power quality analyzer was connected at the monitoring point PCC2. During energy and power quality audit of pune municipal corporation , it is observed that presently only two induction motors (IM1 and IM2, 450 kW each) are used for one of its water pumping facility and want to connect two additional induction motors (IM3 and IM4,450 kW each) of same rating to increase the water pumping capacity. In this case study, simplified assessment methods applied for evaluating the connection of a new IM3 and IM4 induction motor loads to an existing network. As an induction motor is started up, most of the power drawn by the motor is reactive. This results in a large voltage drop across distribution lines. Short term voltage flicker level observed during measurements for Induction motor IM1 and IM2 at PCC are given in Table 3.

Table 3: Short term flicker severity measured for IM1 and IM2

Induction motors (IM1 and IM2)	Short time flicker Measured	Short time flicker at Planning Levels
When does not operate	0.45	0.9
When operate	0.70	0.9

The simulated system with MATLAB/SIMULINK software to study the fuzzy bang-bang controller on flicker mitigation using USSC is shown in Figure 6.

The control structure of USSC used to illustrate the proposed fuzzy bang-bang controller is shown in Figs.7-8. The shunt converter can be controlled for maintaining constant voltage in dc bus and so it is controlled only to maintain dc bus voltage at *th* desired level.

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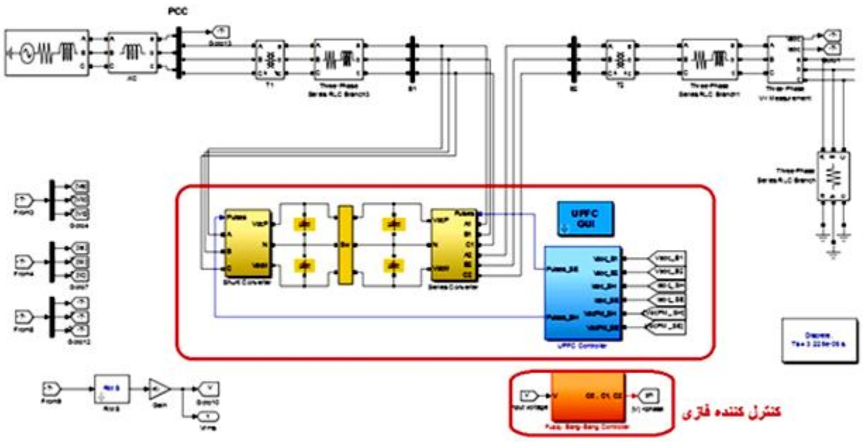

Fig. 6: Simulated system in MATLAB/SIMULINK

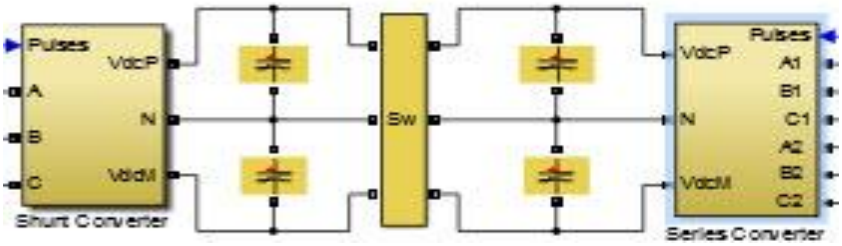

Fig. 7: Series and shunt converters of USSC in MATLAB/SIMULINK

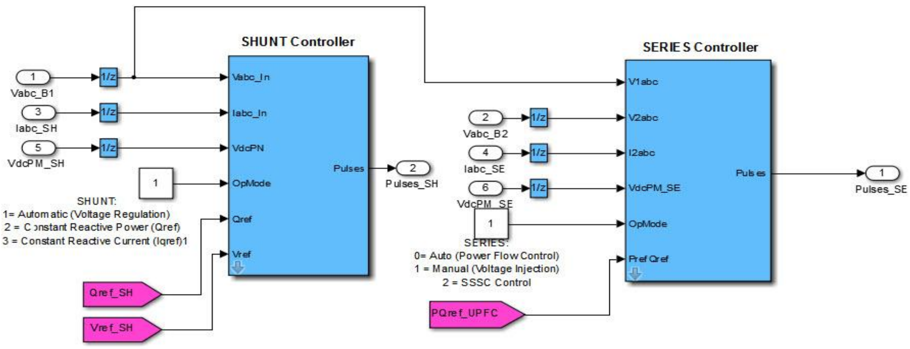

Fig. 8: Fuzzy bang-bang controller designed for USSC

Changing state of switches C0, C1 or C2 as shown in Figure 9 can regulate the voltage injected by the series controller.

Fig. 9: Changing state of switches C0, C1 or C2

Active and Reactive power variation (ΔP and ΔQ) as well as voltage change at PCC2 when all induction motors operate is taken from MATLAB/SIMULINK simulation is shown in Figure 10.

The Figure 11 shows the voltage wave form at PCC2 accurately in smaller interval time.

RMS value of voltage at PCC without USSC is shown in Fig.ure 12.

Active and reactive power variation (ΔP and ΔQ) as well as voltage change at PCC2 when USSC operates using fuzzy bang-bang controller scheme is shown in Figure 13.

RMS value of voltage at PCC with USSC is shown in Figure 14.

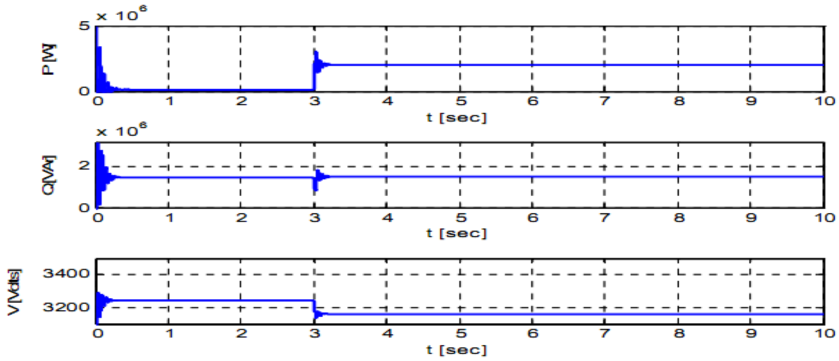

Fig. 10: Simulated results of voltage, reactive and active power variations when four induction motors operates at its full capacity

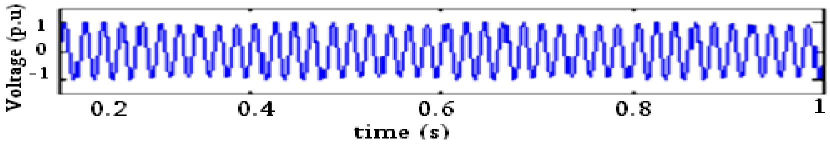

Fig. 11: Voltage wave form at PCC2

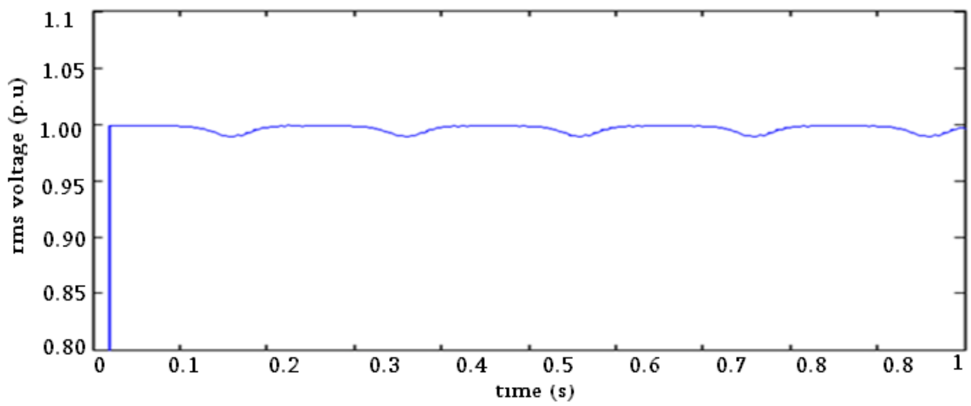

Fig. 12: RMS value of voltage at PCC without USSC

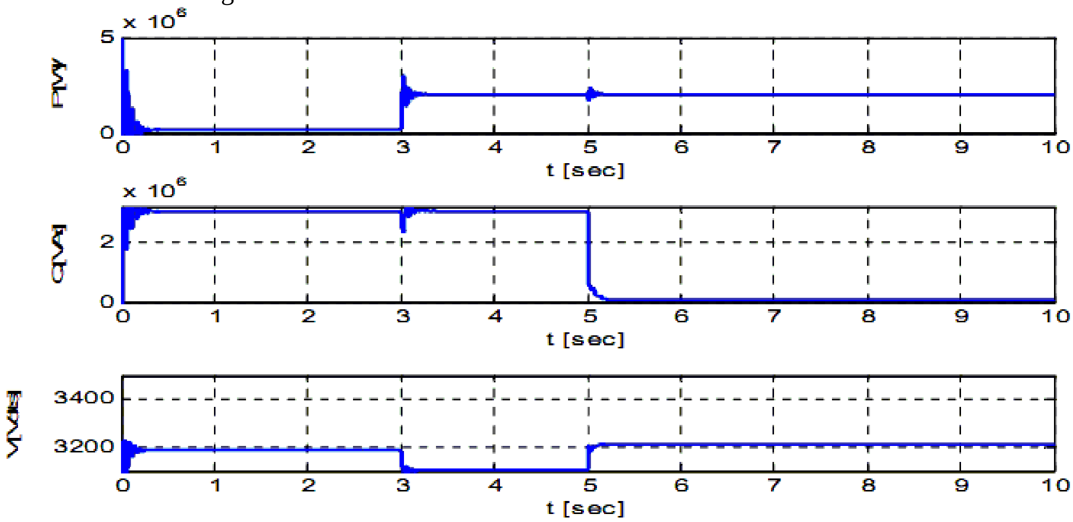

Fig. 13: Simulated results of voltage, reactive and active power variations when four induction motors operates at its full capacity in presence of USSC

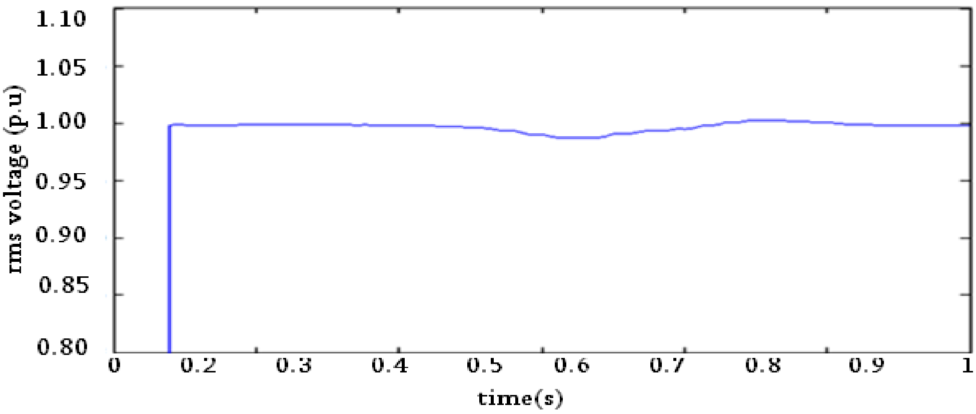

Fig. 14: RMS value of voltage at PCC with USSC

Conclusion:

A new control strategy for flicker mitigation at distribution system due to induction motors starting which are implemented in water pumps is detailed in this paper. In order to test these control strategy, detailed control unit of the USSC is presented and their implementation using MATLAB/SIMULINK demonstrate their excellent characteristics in mitigating flicker. In this paper, USSC controller is derived by using Fuzzy Logic Control (FLC) based on bang-bang control. The model is simulated in MATLAB/SIMULINK platform and USSC controller's performance is evaluated. Numerical simulation proved the effectiveness of the controller in compensating voltage flicker. The results revealed that the USSC gives a better performance in power quality mitigation especially in voltage flicker compensation and power flow control and also provide more power quality solutions as compared to the D-STATCOM shunt capacitor bank, DVR, SVC.

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