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Photovoltaic-Based Static Synchronous Compensator For Voltage Sag Mitigation

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ABSTRACT

A static synchronous compensator (STATCOM) is a fast-acting device that can provide or absorb reactive current, thereby regulating the voltage at the point of connection to a power distribution system. This paper presents a simulation model of a 24-pulse STATCOM using photovoltaic (PV) as a power source for the STATCOM during a deep voltage sag. To achieve a stable characteristic of the STATCOM, a feedback control loop is proposed and employed to achieve a faster response in sag and swell detection and mitigation capability with non-linear loads. Simulation was carried out using the PSCAD/EMTDC electromagnetic transient program to validate the capabilities of the 22/0.4 kV STATCOM in performing voltage sag and swell compensation. The test results show that the proposed controller for the 24-switch pulse inverter with PV source is better than that of the conventional controller. It takes only 2ms for compensation and only 0.99 pu for load restoring.

Keywords: STATCOM, Load restore, Power Quality, Alfa Axis, Beta Axis, Phase Locked Loop

مثبت تعويض متزامن ثابت قائم على الخلايا الكهروضوئية لتخفيف انخفاض الجهد

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ملخـــــــص البحـــــــث

المعوض الستاتيكي التزامني (STATCOM) هو جهاز سريع الاستجابة قادر على تقديم أو امتصاص التيار التفاعلي وبالتالي تنظيم الجهد عند نقطة الاتصال بأنظمة توزيع الطاقة. تعرض هذه الورقة نموذج محاكاة لمقوم STATCOM ذو 24 نبضة باستخدام الطاقة الضوئية (PV) كوسيلة لتوفير مصدر طاقة بديل لـ STATCOM أثناء انخفاض الجهد العميق. لتحقيق خاصية مستقرة للـSTATCOM ، يتم استخدام حلقة التحكم الراجعة لتحقيق استجابة أسرع في اكتشاف الانخفاض والارتفاع في الجهد وقدرة التخفيف مع الأحمال غير الخطية. تم إجراء المحاكاة باستخدام برنامج التحليل

العابر الكهرومغناطيسي PSCAD/EMTDC للتحقق من قدرات الـ STATCOM بجهد 0.4/22 ك.ف في تنفيذ تعويض انخفاض وارتفاع الجهد. تظهر نتائج الاختبار أن وحدة التحكم المقترحة لمقلوب النبض ذو 24 مفتاحًا مع مصدر الطاقة الضوئية أفضل من وحدة التحكم التقليدية، حيث انه تحسن النظام لتعويض في 2 مللي ثانية واستعادة جهد الحمل إلى 0.99 وحدة نسبية.

الكلمات الدالة: المعوض المتزامن الساكن، استعادة الأحمال، جودة الطاقة، محور ألفا، محور بيتا، حلقة قفل الطور.

1. Introduction

The most common power quality problems are the voltage sags and swells[1]. STATCOM is considered an effective custom power device for mitigating the impacts of upstream voltage disturbances on sensitive loads [1,16]. STATCOM can maintain the load voltage at the desired amplitude during the fault duration by injecting a compensating voltage in parallel with the sensitive load terminal voltage. PV-based STATCOM is considered one of the most effective solutions for enhancing the functionality of the PV grid system by adding ancillary functions to the grid side inverter [1,17].

This paper describes the power quality problems such as voltage sag, voltage swell, deep voltage and total harmonic distortion (THD). Voltage sag is the deviation in the magnitude and/or phase of one or more of the phases of a three-phase supply, with respect to the magnitude of the other phases and normal phase angle (120º) and the frequency deviation is a variation in frequency from the nominal supply frequency above/below a predetermined level, normally ± 0.1%. The size and the duration of the frequency shift depend on the load characteristics [2]. The unbalanced voltage can be mitigated using three single-phase STATCOMs [3,16, 17]. The unbalanced voltage has a direct effect on the load and decreases the efficiency of the system. The voltage unbalance may cause excessive current in one or more phases, which causes excessive heating of the diodes and decreases the lifetime of the DC link [4]. The power frequency variation is one of the power quality problems. Power frequency variations are defined as the deviation of the power system fundamental frequency from its specified nominal value (e.g., 50 or 60 Hz) [5]. The duration range of the frequency deviation is between several cycles and several hours, and the maximum tolerable variation in supply frequency is often limited within ± 0.5 Hz. These variations are usually caused by rapid changes in the loads connected to the system. Voltage sags are the most common power problem, which can cause interruptions to sensitive equipment and can occur on multiple phases or on a single phase[6]. The sag is defined as the decrease of the root-mean square(RMS) value of voltage, which can last from half a cycle to one minute [7], and the voltage swell is defined in a similar way, but represented by the increases in the rms value and happens due to sudden load decreases. Sag happens by short circuit, atmospheric, energising of motoring, high power load and welding machines[8]. Asymmetrical faults will cause imbalance and phase shift from the nominal values. Phase angle shift is a change in the phase angle of the voltage/current. Some loads, such as thyristor-based drives, are sensitive to phase-angle shift, which can lead to the wrong determination of the zero crossing of voltage. Harmonic distortion is the change in the waveform of the supply voltage from the ideal sinusoidal waveform, caused by the interaction of distorting customer loads with the impedance of the supply network [8]. The term harmonics refers to the decomposition of a non-sinusoidal but periodic signal into a sum of sinusoidal components, as given by

$$f(t) = \sum_{h=1}^{\infty} A_h \cos\left(2\pi h f_0 + \varphi_h\right) \tag{1}$$

With A_h φ_h amplitude and phase angle for harmonic order h , and T the period. For a power system operation at 50 Hz, any non-sinusoidal voltage or current can be decomposed into a fundamental (50

Hz) component plus a number of harmonic components with frequencies that are multiples of 50 Hz. The latter is called the harmonic components. The 150 Hz component (h = 3) is referred to as the third harmonic, etc. A common way of tackling the harmonic problem is by installing filters, typically LC – filters [9]. Some sensitive electronic loads are negatively affected by high harmonic voltage distortion. The effect on such loads is, however, not so much related to the harmonic spectrum but to the actual waveform, e.g. notching and multiple zero-crossing. Loads also become more sensitive to voltage sags. The Individual Harmonic Distortion (IHD) at a particular harmonic frequency is the ratio of the RMS of the harmonic under consideration to the RMS value of the fundamental, as given by

$$IHD_{Ih} = \frac{I_h}{\sqrt{\sum_{h=1}^{n} I^2{}_h}} \times 100 \tag{2}$$

where

I_h RMS value of current at frequency h

The Total Harmonic Distortion (THD) is defined as the ratio of the RMS sum of all harmonic frequencies to the RMS value of the fundamental frequency and is given by,

$$THD_I = \frac{\sqrt{I_2 + I_3 + ... + I_n}}{\sqrt{I_1 + I_2 + ... + I_n}} \times 100 = \frac{\sqrt{\sum_{h=2}^{n} I_h^2}}{\sqrt{\sum_{h=1}^{n} I_h^2}} \times 100 \tag{3}$$

where

I_1 is the RMS value of the current at the fundamental frequency.

Harmonic distortion for 24-pulse STATCOM can be reduced the THD to 1.52% [10], but in [11], harmonic distortion for 12-pulse STATCOM was reduced to 8.5%.

The control strategy of STATCOM is the heart of a compensator system. Mathnani et al. in [12] proposed a fast two-vector control phase-locked loop to control the phase and frequency of the grid voltage using 48-pulse switching. This controller senses the phase shift of the grid as frequency deviation by the load and locks to the positive sequence. 2-vector control with PLL and dq controller to control 6-pulse STATCOM and control the phase shift between the power system current and source voltage have been proposed in [13], but in [14] a 2-closed loop algorithm to control the performance of the angle between the source voltage and load voltage at 1 p.u.This paper proposed a feedback loop with PLL, PI, αβ and dq to control the PV voltage for the 24-pulse STATCOM during sag, swell and interruption. The rest of the paper presents: the proposed STATCOM design, results and discussion, and the final conclusions.

2. PROPOSED STATCOM DESIGN

The model, as shown in Figure 1, is proposed to improve the power to the load and reduce the harmonic distortion generated from STATCOM. The proposed STATCOM model consists of a control circuit and a power circuit. The control circuit is used to derive the parameters such as magnitude, frequency and phase shift. The power circuit consists of five main units: PV, ESC, STATCOM, and a voltage injection transformer. A simplified test distribution system including STATCOM is implemented using the PSCAD/EMTDC simulations to evaluate the voltage swell and sag mitigation capability of the

STATCOM. The test system comprises a 22 kV transmission system, feeding into the step-down transformer. The STATCOM is placed parallel with the 0.415 kV distribution systems along with the load. The PV on the DC side provides the STATCOM energy requirements during a long sag duration, when the energy of the capacitor is not sufficient.

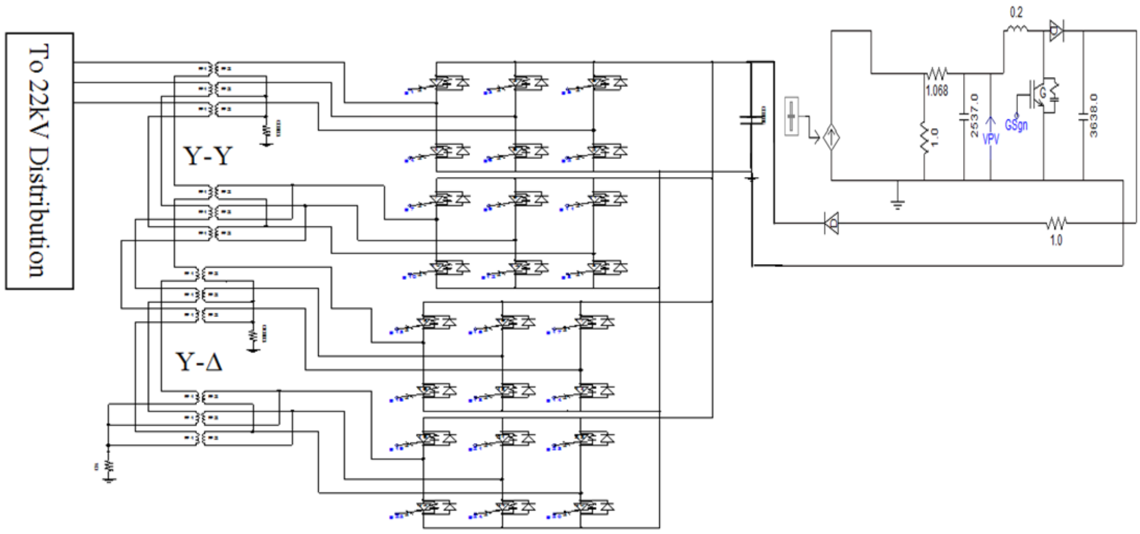

Figure 1. PSCAD Simulation model

The proposed circuit consists of four identical 6-switch inverters connected in parallel to generate a 24-pulse with a phase shift of 15 degrees. The coupling transformer of STATCOM is connected in Y- Δ in the STATCOM side to eliminate the zero-sequence voltage with a leakage reactance of 0.1 p.u.

The STATCOM is connected in parallel with the source and the load and injects AC voltage to the distribution system with controllable magnitude and phase angle. The injected voltage can be considered essentially as a synchronous AC voltage source, and the line current flowing through this voltage source results in real and reactive power exchanging between the STATCOM and AC system. The active power of the STATCOM is supplied by the ESC and injected at the ac terminal. The reactive power of the STATCOM exchanged at the AC terminal is generated and absorbed internally by the power converter. During the no-voltage sag, the STATCOM is not injecting any voltage into the system. In that case, if the ESC is fully charged, then the STATCOM operates in the standby mode, and the supply voltage V_S is identified as pre-sag voltage and denoted by $V_{pre\text{-}sag}$. In such a situation, the load voltage V_L and the supply voltage will be the same. The STATCOM is activated and injects the voltage to the distribution system when a sag, swell or interruption occurs. The magnitude and the phase angle of the supply voltage can be changed. The controller can control the magnitude and angle independently. If the voltage sag is fully compensated by the STATCOM, the load voltage during the voltage sag will be $V_{pre\text{-}sag.}$ PWM controls the active and reactive power that produces voltage to the system. The power is fed from the ESC link. The injected voltage of a STATCOM ($V_{STATCOM}$) can be derived by considering the equivalent circuit of the system shown in Figure 2. When the source is dropped, the STATCOM injects a series voltage through the injection transformer so that the desired voltage magnitude V_L can be maintained. The injected voltage of the STATCOM can be written as

$$V_S = V_X - V_{STATCOM} + V_L \quad (4)$$

Where ;

V_s is the source voltage during sags/swells conditions

V_L is the desired load voltage magnitude

V_X is the impedance voltage

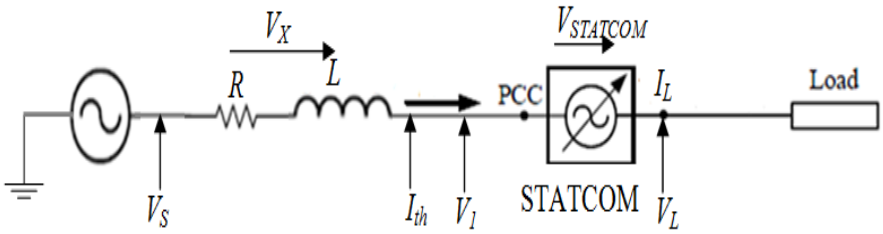

Figure 2. Equivalent circuit of STATCOM

2.1 Energy Storage Unit for the STATCOM

The boost converter in this design is used to back up the STATCOM energy during the sag. As shown in Figure3, the capacitor C_2 can be used as an energy storage device. The ability of the STATCOM compensation is based on the amount of reactive power absorbed /supplied from the system or the active power supplied by the energy storage devices.

During the voltage swell, the energy stored by C_2 is obtained as:

$$C_2 = P_{inj}\, t_{swell} \quad (5)$$

where t_{swell} is the duration of swell.

The injection power with the lagging phase shift is

$$P_{inj} = cos(ø) - (1+\Delta U)cos(ø-\delta) \quad (6)$$

and the injection power with the leading phase shift is

$$P_{inj} = cos(ø) - (1+\Delta U)cos(ø+\delta) \quad (7)$$

where

$Ø$ is the load power factor angle,

Δ is the grid voltage phase angle shift,

$1+\Delta U$ is the magnitude of the voltage swell.

Considering $\delta=0$, the injection power becomes $P_{inj}=-\Delta u cos(ø)$. This means that the source voltage does not change due to the voltage swell. The compensation capacity of STATCOM depends on the maximum voltage injection ability and the active power which can be supplied by the STATCOM. The equation (1-7) can be found in [13].

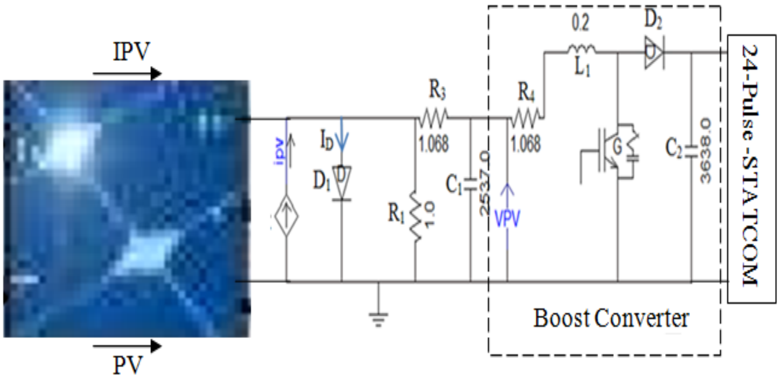

Figure 3. Modelling with a boost converter

2.2 STATCOM Capacitor Sizing

STATCOM capacitor sizing, as shown in Figure 1, plays an important role in the STATCOM. It acts as a DC source to provide reactive power to the load during fault conditions. The capacitor should be charged at all times to keep the compensation voltage at 1 p.u. To determine the DC capacitor size, C_{dc}, firstly consider the energy stored in the capacitor in one period as,

$$\Delta E_c(t) = \frac{C_{dc}}{2}\left(V^2{}_{c,\max} - V^2{}_{dc}\right) \tag{8}$$

$V_{c,\,max}$ is the pre-set upper limit of the voltage across the capacitor
V_{dc} is the voltage across the capacitor
C_{dc} is the DC capacitor
The energy loss is also supplied by the utility voltage source, V_s and the peak value of the charging current, I_{sc}, in which the energy loss can be written as,

$$\Delta E_c(t) = \int_0^T V_S \sin \omega t I_{SC} \sin \omega t dt \tag{9}$$

Simplifying Equation (9)

$$\Delta E_C(t) = V_S I_{SC} \int_0^T \sin^2 \omega t dt = V_S I_{SC}\left[\frac{t}{2} - \frac{\sin 2\omega t}{2\omega}\right]_0^T \tag{10}$$

$$\Delta E_c(t) = \frac{1}{2} V_S . I_{SC} . T \tag{11}$$

where,
V_S is the peak phase voltage of the STATCOM
T is the period of one cycle
Equations (8) and (11) give,

$$\frac{C_{dc}}{2}(V^2{}_{C,\max} - V^2{}_{dc}) = \frac{1}{2} V_S I_{SC} T \tag{12}$$

The following equation is used to determine the size of the capacitor, C_{DC},

$$\frac{1}{2}C_{DC}\left[V^2{}_{C\max}-V^2{}_{dc}\right]=\frac{1}{2}V_s\Delta I_{Li}T \tag{13}$$

where

V_{dc} is the preset lower limit voltage of the energy storage capacitor.

ΔI_{Li} is the step increase of the peak value of the real fundamental component of the load current.

T is the period of the utility voltage source.

Using equation (13), the DC capacitor value for a three-phase system can be derived and given as,

$$C_{dc}=3\frac{V_S\Delta I_L T}{V_{C\max}^2-V_{dc}^2} \tag{14}$$

where

Vs is the peak phase voltage

I_L is the step-drop of load current

T is the period of one cycle of voltage and current

V_{Cmax} is the pre-set upper limit of the energy storage C (per-phase),

V_{dc} is the voltage across C (per-phase).

The value of can be found by measuring the load current before and during the voltage sag.

The value of V_{dc} is given by

$$V_{dc}=\frac{3\sqrt{3}.Vs\cos\alpha}{\pi} \tag{15}$$

where

α = delay angle. If α=0, the equation becomes,

$$V_{dc}=\frac{3\sqrt{3}}{\pi}V_s \tag{16}$$

The derivation of V_{dc} and Equation (15) can be found in [12]. From Equation (14), the capacitance value as shown in Figure1 is 4220μF, which is connected in parallel to increase the energy storage and to reduce the ripple on the DC link voltage.

3. STATCOM CONTROLLER DESIGN

The main parts of the controller, PLL, PI, αβ and dq are used for interpolated firing pulses as shown in Figure 4. The maximum block abc/αβ receives the measured voltage values V_{s1}, V_{s2} and V_{s3} in per unit(Vp.u), which is then passed to the filter to attenuate the voltage transient. PLL and αβ / dq are compared and passed to the PI controller. The function of the PI control block is to minimise the steady state error of the load voltage zero. The angle is necessary to control the magnitude and phase to get a modulating voltage signal.

4. Results and Discussion

The designed STATCOM and the controller have been simulated in order to mitigate power quality problems, which are voltage sag, voltage swell and voltage interruption. The controller is designed to compensate for the system, even with a nonlinear load without harmonics and delay. Figure 5 shows the system during the sag and compensation in the load at the start and end of events. At time t = 0.5 ms, the voltage sag is initiated, and the supply voltage is restored 0.5 ms later. At time t =1 ms, the supply jumps back to the pre-sag condition. The nonlinear load in this design is not affected during the sag and

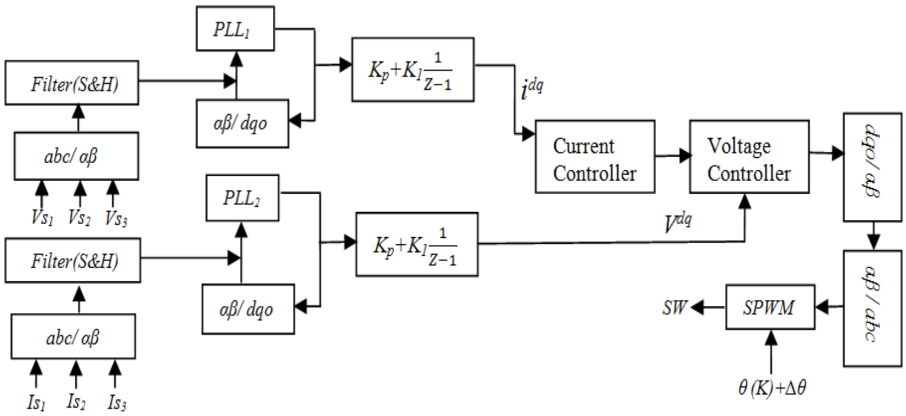

Figure 4. Voltage source inverter arrangements

remains at 0.99 p.u (~1 p.u), and also the figures show that there is no angle shift during the sag. During the sag, the system can be detected and compensated with a very fast response. The STATCOM can sense the sag in point 0.502 p.u at a time near 0.500 sec when the sag starts. Also, the figures show that the start and the end of compensation voltage are in phase with the source voltage and load voltage, respectively. These figures displayed that the compensation is within 2 ms without any harmonic distortion and phase shift during the sags. The new controller designed can improve the in-phase compensation technique during the nonlinear load when compared to the conventional controller.

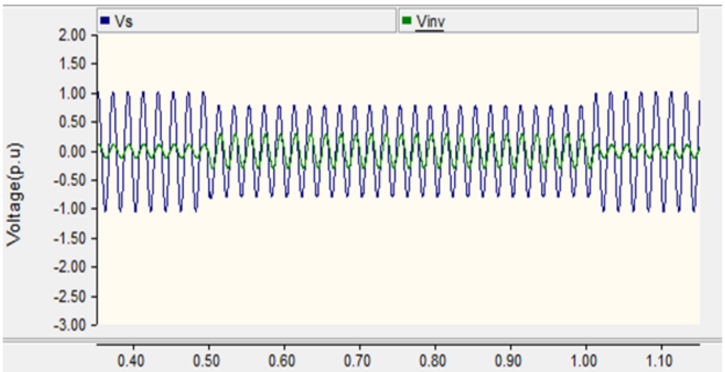

Figure 5. Source voltage (VS) during sag (between 0.5 and 1.0 seconds) and compensation voltage (Vinv) of the simulation

The STATCOM can also operate in UPS mode. Figure 6 shows the deep sag simulation result, which is created at time t = 0.5 sec for a duration of 0.5 sec using a three-phase fault generator. As shown in Figure 7, when the STATCOM is connected in the system with an external DC source, it can recover the load voltage from 0.001 to 0.99 p.u within a 2-ms response and without any transient voltage during the recovery moment. Stead-state performance is obtained by the feedback control loop compared to the conventional control. The proposed controller contains a closed loop with PLL, PI controller and DQ0. This controller can mitigate the sag in steady-state conditions.

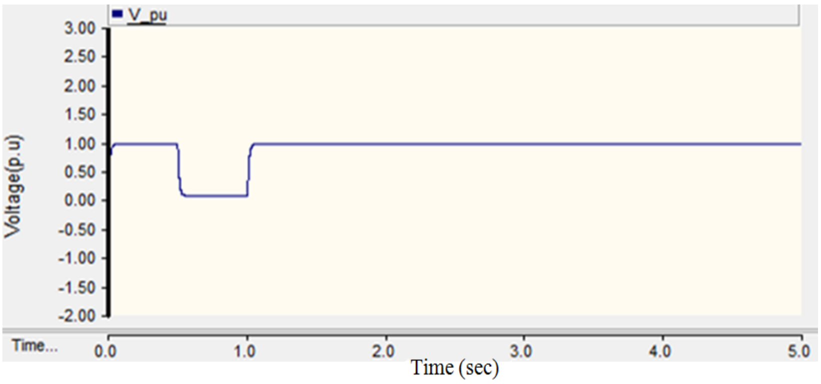

Figure 6. Deep sag on the load

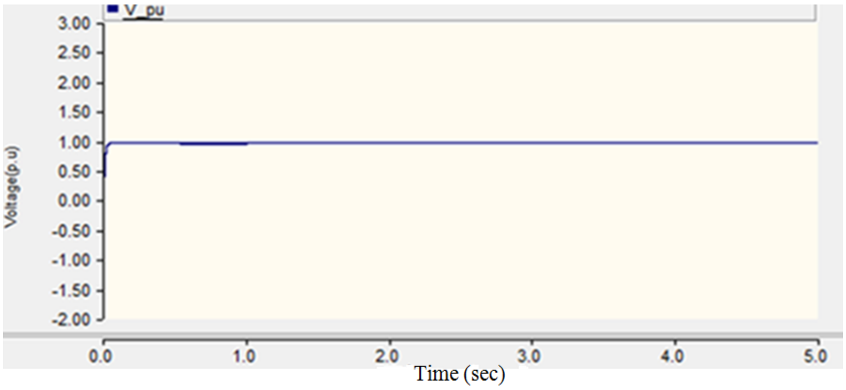

Figure 7. Load voltage compensation

4.1 Fast Compensation for Non-Linear Load

The feedback controller proposed in this work can improve the response of the dc magnitude and time to track the phase angle during all steps of the system to keep the system at a steady state response. During the sag, the dc voltage magnitude does not decay due to the injection of the active power into the system. The DC magnitude during the sag and compensation is depicted in Figure 8. The delay between the magnitude of the DC source and the source voltage is equal to zero, because of the fast response of the controller design, and the STATCOM can inject exact power during the sag. The DC magnitude is obtained by connecting the external source directly to the STATCOM with the ESC. The control algorithm is designed to sense the sag and the DC source at the same time to keep the DC level at the exact level. The design can control the reactive power and minimise the active power to keep the load voltage magnitude at 1 p.u. The minimisation of active power injection is to increase the life of the energy storage system.

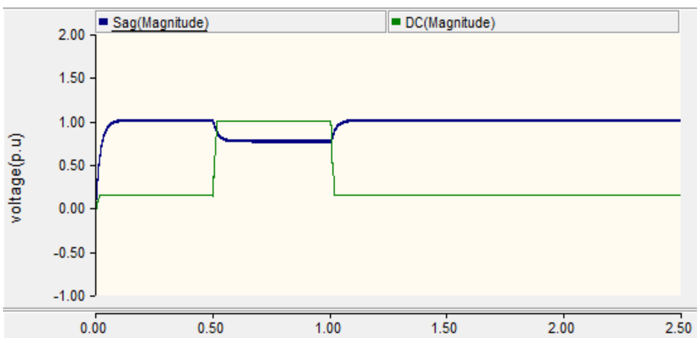

Figure 8. Magnitude of DC voltage and voltage during the sag

4.2. Voltage Swell Protection Mitigation

In case of a voltage swell, active power may be drawn from the source into the ESC of the STATCOM. Figure 9 shows a voltage swell where the voltages of the supply are programmed to have 22% voltage swell, and Figure 10 shows the compensated voltage. It can be noted from Figure 11 that the STATCOM can keep the load voltage constant in all the measured cases near 1p.u..

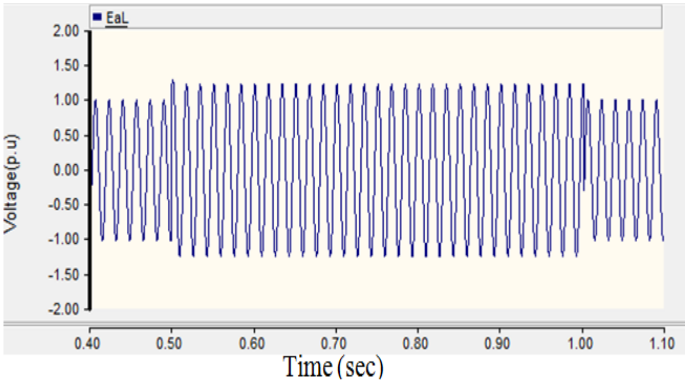

Figure 9. Voltages swell with a non-linear load

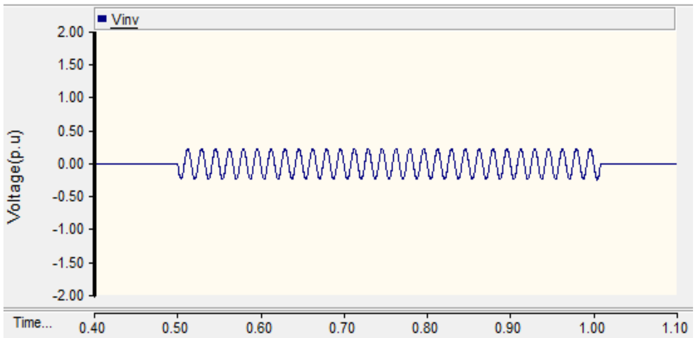

Figure 10. Injected voltage

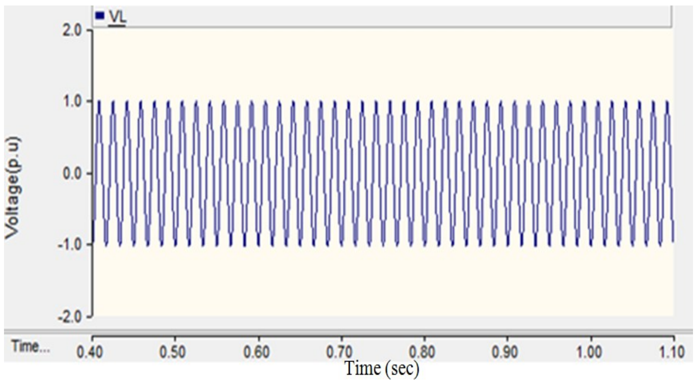

Figure 11. Load voltage

Figure 12 and 13 show the THD value of the system without and with the filter, respectively. The figures show that the THD is reduced from 7.15% to 0.02% with the filter that is connected at the primary and secondary of the transformer and PV that is connected as an external DC source. The THD of 0.02 is far below the value of the IEEE standard THD limit of 5%. The curves would change if the

PV source value is changed. This implies that increasing external DC source voltage may improve the capability that STATCOM and can cope with more severe sags; however, depending on the firing control scheme and other factors, harmonics injected into power system may differ. If the gains of the PI controller are selected properly, the PLL will behave as a low pass filter. Thus, harmonics in the source voltage may not affect the performance of the PLL. The results show that the new efficient STATCOM can provide excellent voltage without harmonic distortion.

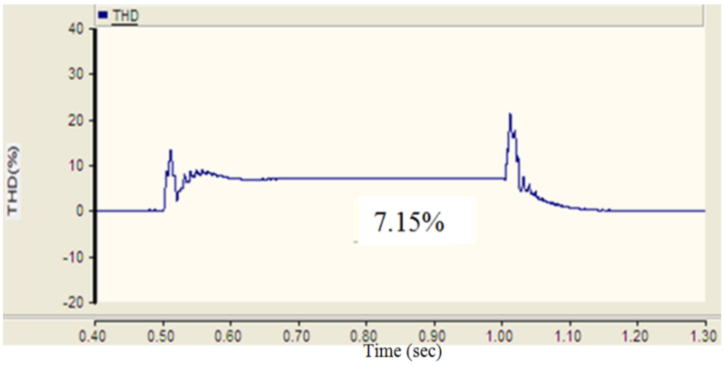

Figure 12. Total harmonic distortions during sag

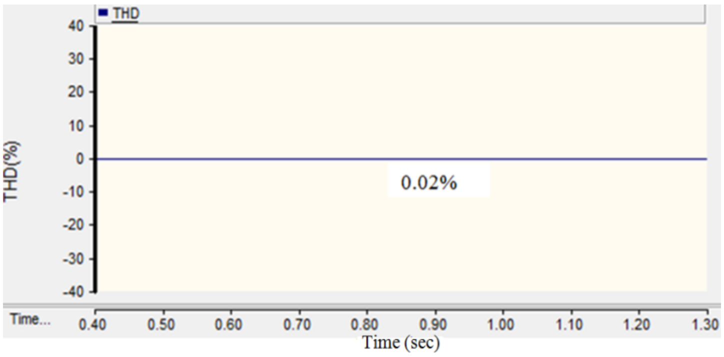

Figure 13. Total harmonic distortions during compensation

5. Conclusions

24-pulse STATCOM is a custom device connected in parallel to the distribution system to protect the system from the voltage sag, voltage swell and deep sag. In this work, the modelling and simulation of a STATCOM with the necessary control system using PSCAD are presented. A novel design of the controller has been developed to force the injection voltage to be in-phase with the load voltage and source voltage. The new controller can restore the load voltage to 0.99 p.u for a nonlinear load. The simulation results show that the 24-pulse STATCOM compensates the voltage sag/swell quickly and provides excellent voltage regulation without harmonic distortion. The load voltage has been maintained, and the active power usage has been minimised by the 24-statcom STATCOM. Using these control strategies improves the system efficiency. From the results, it can be seen that the feedback controller is effective in tracking the phase, the harmonic and compensates the system within a fast response time (2 ms) under various operating conditions in case of non-linear load. Also, the controller design can charge the ESC in two directions by acting like an AC-DC converter during normal operation and as a DC-AC converter during disturbances. Above all, the new design also increases the life of the ESC. Finally, an external energy is connected to the STATCOM to avoid voltage decay during the sag.

SUMMARY OF THE CONTRIBUTIONS

This work has developed a STATCOM to mitigate the voltage sag, swell and deep sag. Using a new controller for the 24-pulse STATCOM. The new design of the controller can improve the response to 2 ms and the active power of 0.1 kW. The injection power is improved, and the DC link voltage does not decay during the sag when the PV is connected to the ESC.

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