POWER QUALITY ENHANCEMENT IN ELECTRIFIED TRAMS BY USING A HYBRID ACTIVE FILTER

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ABSTRACT

This paper presents a transformer less hybrid series active filter is proposed to enhance the power quality in single-phase systems with critical loads. The energy management and power quality issues related to electric transportation and focuses on improving electric vehicle load connection to the grid. The control strategy is designed to prevent current harmonic distortions of nonlinear loads to flow into the utility and corrects the power factor of this later. While protecting sensitive loads from voltage disturbances, sags, and swells initiated by the power sys- tem, ridded of the series transformer, the Configuration is advantageous for an industrial implementation. This polyvalent hybrid topology allowing the harmonic isolation and compensation of voltage distortions could absorb or inject the auxiliary power to the grid. Aside from practical analysis, this paper also investigates on the influence of gains and delays in the real-time controller stability. The simulations results presented in this paper demonstrating the effectiveness of the proposed topology using MATLAB software.

Keyword: - *Multi-carrier PWM Techniques, Current harmonics, electric vehicle, hybrid series active filter (HSeAF), power quality, real-time control*

1. INTRODUCTION

One of the major concerns in electricity industry today is power quality problems to sensitive loads. Presently, the majority of power quality problems are due to different fault conditions. These conditions cause voltage sag. Voltage sag may cause the apparatus tripping, shutdown commercial, domestic and industrial equipment, and miss process of drive system. The proposed system can provide the cost effective solution to mitigate voltage sag by establishing the appropriate voltage quality level, required by the customer. It is recently being used as the active solution. To overcome the problem related to the power quality custom power device is introduced. A number of power quality problem solutions are provide by custom devices. At present, a wide range of flexible AC controller which is capitalized on newly available power electronic components is emerging for custom power application.

The future Smart Grids associated with electric vehicle charging stations has created a serious concern on all aspects of power quality of the power system, while widespread electric vehicle battery charging units [1], [2] have detrimental effects on power distribution system harmonic voltage levels [3]. On the other hand, the growth of harmonics fed from nonlinear loads like electric vehicle propulsion battery chargers [4], [5], which indeed have detrimental impacts on the power system and affect plant equipment, should be considered in the development of modern grids. Likewise, the increased rms and peak value of the distorted current waveforms increase heating and losses and cause the failure of the electrical equipment. Such phenomenon effectively reduces system efficiency and should have properly been addressed [6], [7]. Moreover, to protect the point of common coupling (PCC) from voltage distortions, using a dynamic voltage restorer (DVR) function is advised.

A solution is to reduce the pollution of power electronics-based loads directly at their source. Although several attempts are made for a specific case study, a generic solution is to be explored. There exist two types of active power devices to overcome the described power quality issues. The first category is series active filters (SeAFs), including hybrid-type ones. They were developed to eliminate current harmonics produced by nonlinear load from the power system. SeAFs are less scattered than the shunt type of active filters [8], [9]. The advantage of the SeAF compared to the shunt type is the inferior rating of the compensator versus the load nominal rating [10]. However, the complexity of the configuration and necessity of an isolation series transformer had decelerated their industrial application in the distribution system. The second category was developed in concern of addressing voltage issues on sensitive loads. Commonly known as DVR, they have a similar configuration as the SeAF. These two categories are different from each other in their control principle. This difference relies on the purpose of their application in the system.

The hybrid series active filter (HSeAF) was proposed to address the aforementioned issues with only one combination. Hypothetically, they are capable to compensate current harmonics, ensuring a power factor (PF) correction and eliminating voltage distortions at the PCC [11], [12]. These properties make it an appropriate candidate for power quality investments. The three-phase SeAFs are well documented [13], [14], whereas limited research works reported the single-phase applications of SeAFs. In this paper, a single-phase transformerless HSeAF is proposed and capable of cleaning up the grid-side connection bus bar from current harmonics generated by a nonlinear load [15]. With a smaller rating up to 10%, it could easily replace the shunt active filter [16]. Furthermore, it could restore a sinusoidal voltage at the load PCC.

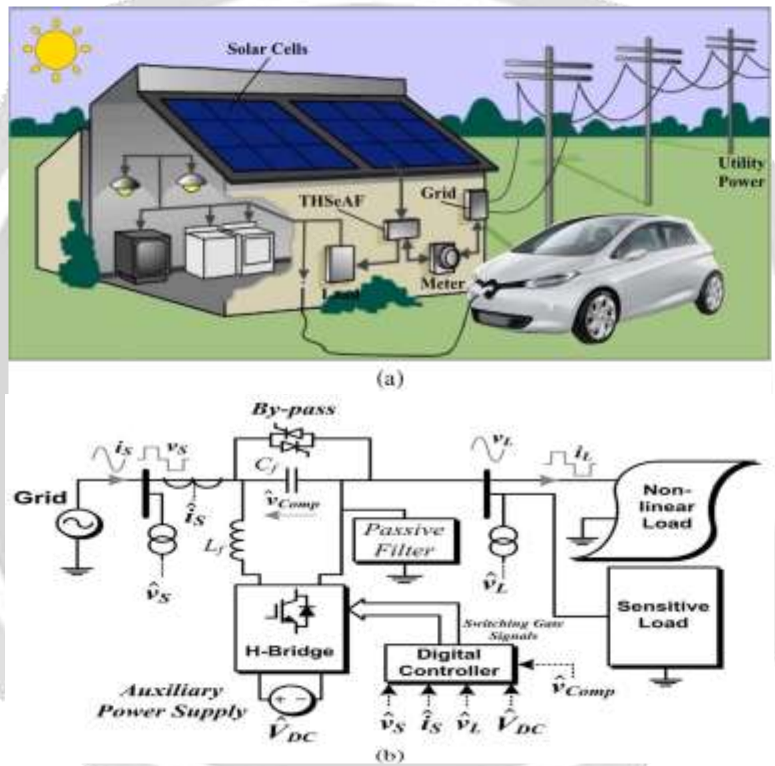

Fig-1: (a) Schematic of a single-phase smart load with the compensator installation. (b) Electrical diagram of the THSeAF in a single-phase utility.

2. EQUIVALENT PHOTOVOLTAIC ARRAY

PV array's output current-voltage curve reflects PV array's dependence on environmental conditions such as ambient temperature and illumination level. Typically, the illumination level ranges from 0 to 1100Wb/m2 and the temperature range is between 233 and 353 K. Normally, we select 1100 and 298 as the reference values for illumination level and temperature respectively. The relationship between PV array's output characteristics and environmental conditions could be illustrated from general simulation results of PV array. PV array's output power is increased as illumination level increases, while PV array's output power is improved with the decrease of the ambient temperature. The equivalent circuit of a typical PV-cell is given below.

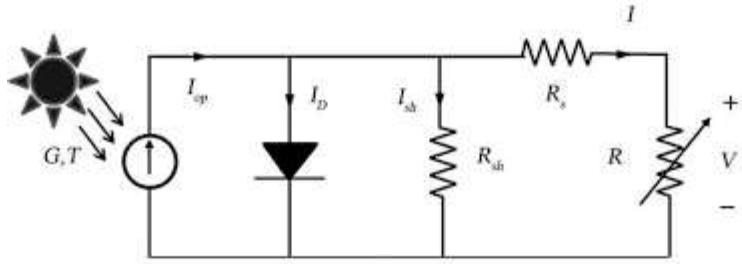

Fig-1: Equivalent circuit of photovoltaic cell

Figure reflects a simple equivalent circuit of a photovoltaic cell. The current source which is driven by sunlight is connected with a real diode in parallel. In this case, PV cell presents a p-n junction characteristic of the real diode. The forward current could flow through the diode from p-side to n-side with little loss. However, if the current flows in reverse direction, only little reverse saturation current could get through. All the equations for modelling the PV array are analysed based on this equivalent circuit.

Boost power converters have been widely used for Power Factor Correction (PFC) in AC-DC conversion and for power management in battery powered DC-DC conversions. Moving beyond low-power applications, such as cellular phones, smart phones and other portable electronic products, boost converters are being used more and more in medium-power applications. For example, in computing and consumer electronics, boost converter-based LED drivers for notebook displays, LCD TVs and monitors have been developed. In communications and industrial products, simple boost converters are used in satellite dish auxiliary power supplies and peripheral card supplies. As boost converters run to CCM (Continuous Conduction Mode), a complex pole pair and a Right-Half Plane (RHP) zero will present in the dynamic characteristic. Some applications of boost converter:

- Programmable soft turn-on for inrush current control
- Hiccup mode for over-current protection
- Complete shutdown with source-load separation
- Simple loop compensation
- Protection for power MOSFET (Q_2) failure

3. TOPOLOGY AND OPERATION PRINCIPLE OF THE PROPOSED CONVERTER

The THSeAF shown in Fig. 4.1 is composed of an H-bridge converter connected in series between the source and the load. A shunt passive capacitor ensures a low impedance path for current harmonics. A dc auxiliary source could be connected to inject power during voltage sags.

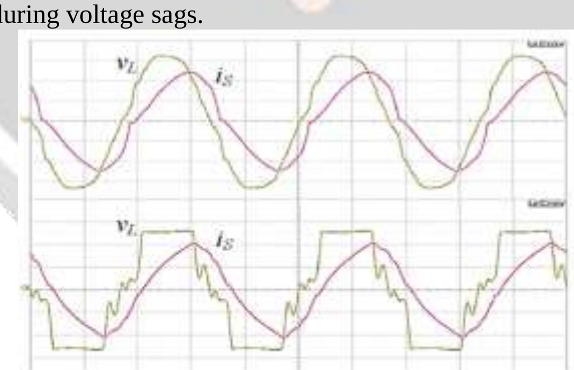

Fig-2: Terminal voltage and current waveforms of the 2-kVA single phase system without compensator. (a) Regular operation. (b) Grid's voltage distortion

The dc-link energy storage system is described in [19]. The system is implemented for a rated power of 2200 VA. To ensure a fast transient response with sufficient stability margins over a wide range of operation, the controller is implemented. The system parameters are identified in Table I. A variable source of 120 Vrms is connected to a 1.1-kVA nonlinear load and a 998-VA linear load with a 0.46 PF. The THSeAF is connected in series in order to inject the compensating voltage. On the dc side of the compensator, an auxiliary dc-link energy storage system is installed. Similar parameters are also applied for practical implementation.

HSeAFs are often used to compensate distortions of the current type of nonlinear loads. For instance, the distorted current and voltage waveforms of the nonlinear system during normal operation and when the source voltage became distorted are depicted in Fig. 4.2. The THSeAF is bypassed, and current harmonics flowed directly into the grid. As one can perceive, even during normal operation, the current harmonics (with a total harmonic distortion (THD) of 12%) distort the PCC, resulting in a voltage THD of 3.2%. The behavior of the system when the grid is highly polluted with 19.2% of THD is also illustrated.

The proposed configuration could be solely connected to the grid with no need of a bulky and costly series injection transformer, making this topology capable of compensating source current harmonics and voltage distortion at the PCC. Even if the number of switches has increased, the transformerless configuration is more cost-effective than any other series compensators, which generally uses a transformer to inject the compensation voltage to the power grid. The optimized passive filter is composed of 5th, 7th, and high pass filters. The passive filter should be adjusted for the system upon load and government regulations. A comparison between different existing configurations is given in Table II. It is aimed to point out the advantages and disadvantages of the proposed configuration over the conventional topologies. To emphasize the comparison table fairly, the equivalent single phase of each configuration is considered in the evaluation. Financial production evaluation demonstrated a 45% reduction in component costs and considerable reduction in assembly terms as well.

3.1 OPERATION PRINCIPLE

The SeAF represents a controlled voltage source (VSI). In order to prevent current harmonics *iLh* to drift into the source, this series source should present low impedance for the fundamental component and high impedance for all harmonics as shown in Fig. 4.3. The principle of such modeling is well documented in [20].

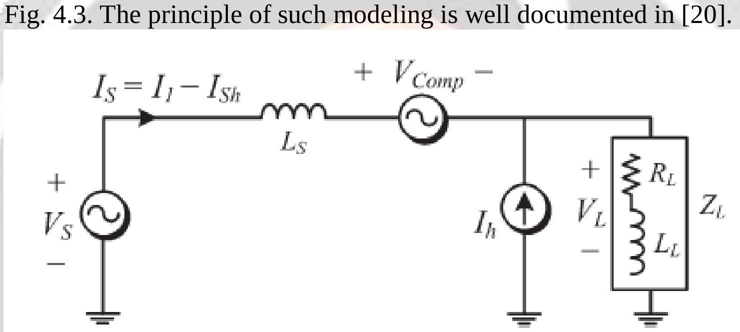

Fig-3: THSeAF equivalent circuit for current harmonics.

The use of a well-tuned passive filter is then mandatory to perform the compensation of current issues and maintaining a constant voltage free of distortions at the load terminals. The behavior of the SeAF for a current control approach is evaluated from the phasor's equivalent circuit shown in Fig. 4.3. The nonlinear load could be modeled by a resistance representing the active power consumed and a current source generating current harmonics. Accordingly, the impedance *ZL* represents the nonlinear load and the inductive load. The SeAF operates as an ideal controlled voltage source (*V* comp) having a gain (***G***) proportional to the current harmonics (*Ish*) flowing to the grid (*Vs*)

$$V_{\text{comp}} = G.I_{sh} - V_{Lh}. \qquad (1)$$

This allows having individual equivalent circuit for the fundamental and harmonics

$$V_{\text{source}} = V_{s1} + V_{sh}, \qquad V_L = V_{L1} + V_{Lh}. \qquad (2)$$

The source harmonic current could be evaluated

$$V_{sh} = -Z_s.I_{sh} + V_{\text{comp}} + V_{Lh} \qquad (3)$$
$$V_{Lh} = Z_L(I_h - I_{sh}). \qquad (4)$$

Combining (3) and (4) leads to (5)

$$I_{sh} = \frac{V_{sh}}{(G - Z_s)}. \qquad (5)$$

If gain ***G*** is sufficiently large (*G*→∞), the source current will become clean of any harmonics (*Ish* → 0). This will help improve the voltage distortion at the grid side. In this approach, the THSeAF behaves as high-impedance open circuit for current harmonics, while the shunt high-pass filter tuned at the system frequency creates a low-impedance path for all harmonics and open circuit for the fundamental; it also helps for PF correction.

3.2 MODELING AND CONTROL OF THE SINGLE-PHASE THSeAF

Based on the average equivalent circuit of an inverter [23], the small-signal model of the proposed configuration can be obtained as in Fig. 4. Hereafter, *d* is the duty cycle of the upper switch during a switching period, whereas ¯*v* and ¯*i* denote the average values in a switching period of the voltage and current of the same leg. The mean converter output voltage and current are expressed by (6) and (7) as follows

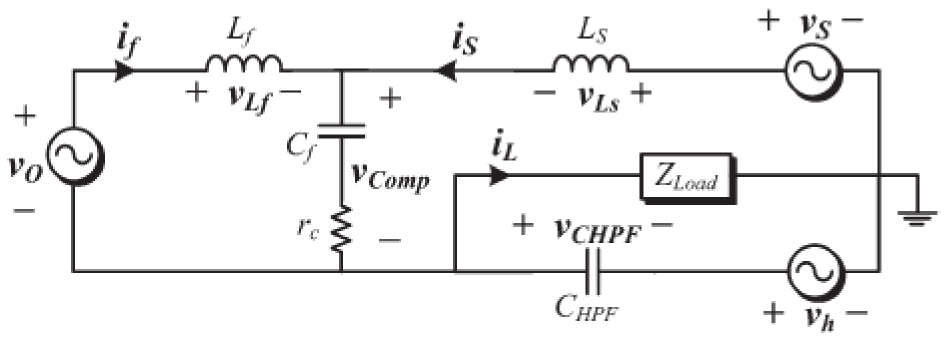

Fig-4: Small-signal model of transformerless HSeAF in series between the grid and the load.

$$\bar{v}_O = \underbrace{(2d-1)}V_{\mathrm{DC}} \qquad (6)$$

Where the $(2d - 1)$ equals to *m*, then

$$\bar{i}_{\mathrm{DC}} = m\bar{i}_f. \qquad (7)$$

Calculating the Thevenin's equivalent circuit of the harmonic current source leads to the following assumption:

$$\bar{v}_h(j\omega) = \frac{-j\bar{i}_h}{C_{HPF}\cdot\omega_h}. \qquad (8)$$

If the harmonic frequency is high enough, it is possible to assume that there will be no voltage harmonics across the load. The state-space small-signal ac model could be derived by a liberalized perturbation of the averaged model as follows:

Hence, we obtain

$$\frac{d}{dt}\begin{bmatrix}\bar{v}_{Cf}\\ \bar{v}_{CHPF}\\ \bar{i}_S\\ \bar{i}_f\\ \bar{i}_L\end{bmatrix} = \begin{bmatrix}0 & 0 & \frac{1}{C_f} & \frac{1}{C_f} & 0\\ 0 & 0 & \frac{1}{C_{HPF}} & 0 & -1/C_{HPF}\\ -1/L_S & -1/L_S & -r_c/L_S & -r_c/L_S & 0\\ -1/L_f & 0 & -r_c/L_f & -r_c/L_f & 0\\ 0 & \frac{1}{L_L} & 0 & 0 & -R_L/L_L\end{bmatrix} \times \begin{bmatrix}\bar{v}_{Cf}\\ \bar{v}_{CHPF}\\ \bar{i}_S\\ \bar{i}_f\\ \bar{i}_L\end{bmatrix} + \begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ \frac{1}{L_S} & 0 & \frac{1}{L_S}\\ 0 & \frac{m}{L_f} & 0\\ 0 & 0 & -1/L_L\end{bmatrix} \times \begin{bmatrix}\bar{v}_S\\ V_{\mathrm{DC}}\\ \bar{v}_h\end{bmatrix}. \qquad (10)$$

Moreover, the output vector is

$$y = Cx + Du \qquad (11)$$

By means of (10) and (12), the state-space representation of the model is obtained as shown in Fig. 4.4 The transfer function of the compensating voltage versus the load voltage, *TV _CL*(s), and the source current, *TCI* (s), are developed in the Appendix. Meanwhile, to control the active part independently, the derived transfer function should be autonomous from the grid configuration. The transfer function *TVm* presents the relation between the output voltages of the converter versus the duty cycle of the first leg converter's upper switch

$$T_V(s) = \frac{V_{\mathrm{comp}}}{V_O} = \frac{r_C C_f s + 1}{L_f C_f s^2 + r_C C_f s + 1} \qquad (13)$$

$$T_{Vm}(s) = \frac{V_{\mathrm{comp}}}{m} = V_{DC}\cdot T_V(s). \qquad (14)$$

The further detailed derivation of steady-state transfer functions is described. A dc auxiliary source should be employed to maintain an adequate supply on the load terminals. During the sag or swell conditions, it should absorb or inject power to keep the voltage magnitude at the load terminals within a specified margin. However, if the compensation of sags and swells is less imperative, a capacitor could be deployed. Consequently, the dc-link voltage across the capacitor should be regulated as demonstrated in Fig. 5.

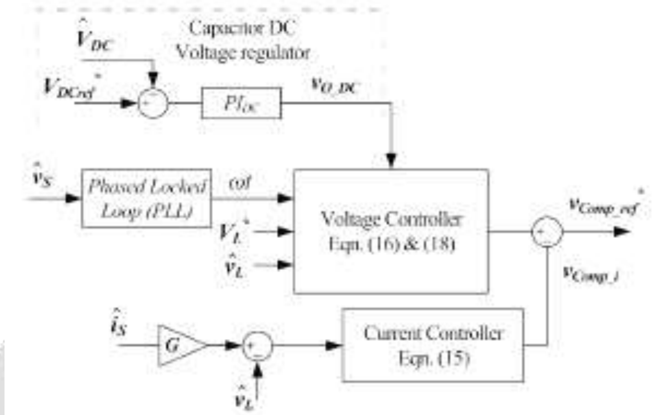

Fig-5: Control system scheme of the active part.

A phase-locked loop was used to obtain the reference angular frequency (ωs). Accordingly, the extracted current harmonic contains a fundamental component synchronized with the source voltage in order to correct the PF. This current represents the reactive power of the load. The gain *G* representing the resistance for harmonics converts current into a relative voltage. The generated reference voltage $v$comp_*i* required to clean the source current from harmonics is described in (15). According to the presented detection algorithm, the compensated reference voltage $v*$ Comp_ref is calculated. Thereafter, the reference signal is compared with the measured output voltage and applied to a PI controller to generate the corresponding gate signals as in Fig.6

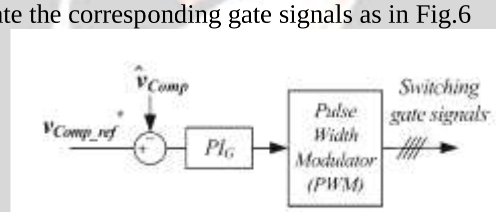

Fig-6: Block diagram of THSeAF and PI controller.

4. RESULTS AND ANALYSIS

The simulation of the proposed DVR system is designed using MATLAB software for analysis. The power quality issues such as Voltage sag, swell and Harmonics are major issues of the present day power system which deteriorates the quality of power. In order to mitigate these issues a simplified FACTS based DVR system has proposed which is connected in series with the line as shown in the figure 7. The power quality issues such as sag, swell and harmonics are dealt with DVR in this work. Initially sag has appeared in the line is at 0.3 seconds to 05 seconds can be seen in figure 11 is mitigated by supplying amount of compensation voltage component in series with the line, similarly swell and harmonics are observed at 0.8 to 1 seconds and 1.2 to 1.4 seconds respectively are dealt with DVR. The DVR with proposed controller has working well during all conditions of the system. A transformerless HSeAF for power quality improvement was developed. The paper highlighted the fact that, with the ever increase of nonlinear loads and higher exigency of the consumer for a reliable supply, concrete actions should be taken into consideration for future smart grids in order to smoothly integrate electric car battery chargers to the grid. The key novelty of the proposed solution is that the proposed configuration could improve the power quality of the system in a more general way by compensating a wide range of harmonics current, even though it can be seen that the THSeAF regulates and improves the PCC voltage. Connected to a renewable auxiliary source, the topology is able to counteract actively to the power flow in the system. This essential capability is required to ensure a consistent supply for critical loads.

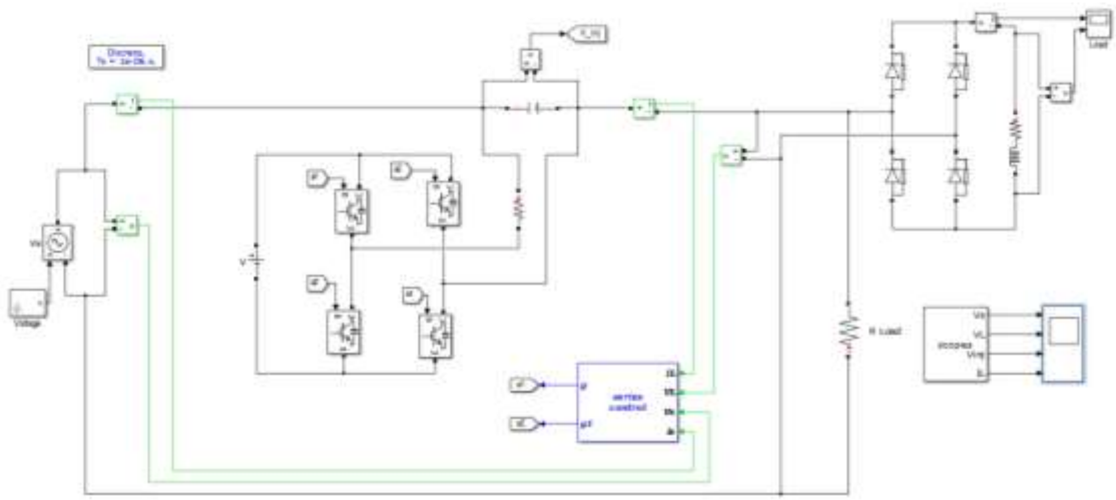

Fig-7: Block diagram of the proposed system using MATLAB software

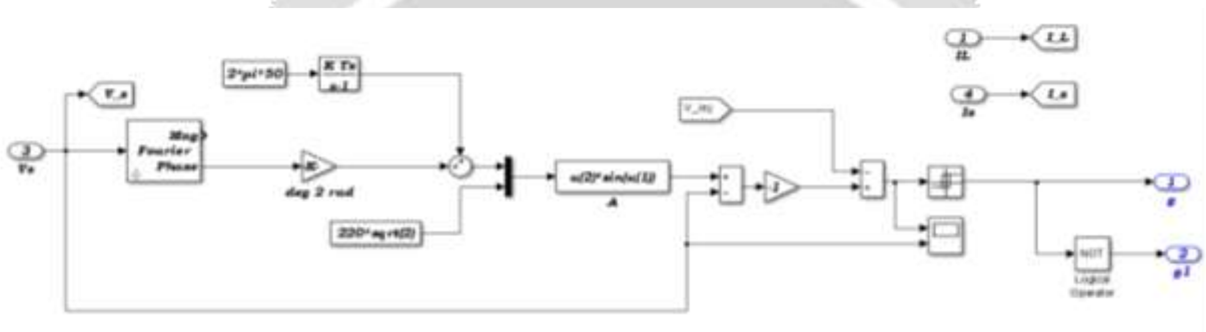

Fig-8: proposed control system design of DVR

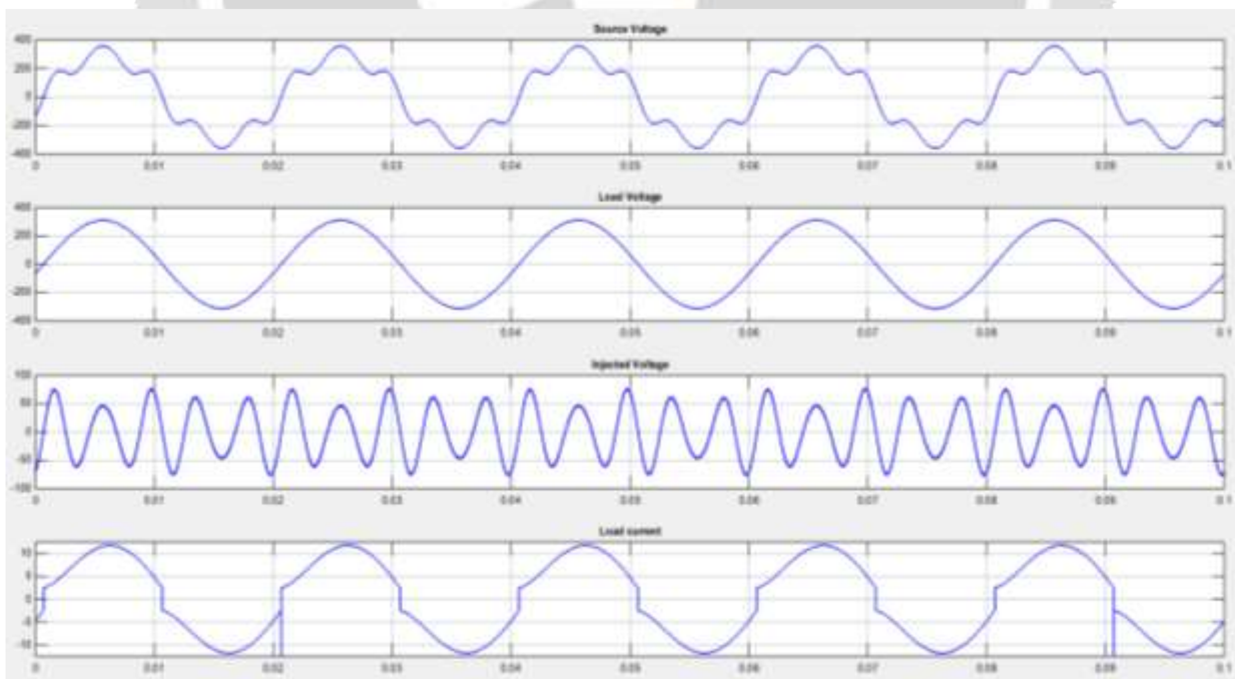

Fig-9: Simulation of the system with the THSeAF compensating current harmonics and voltage regulation. (a) Source voltage *vS*, (b) load voltage *vL*, (c) active-filter voltage *V*Comp, and (d) load current *iL*,

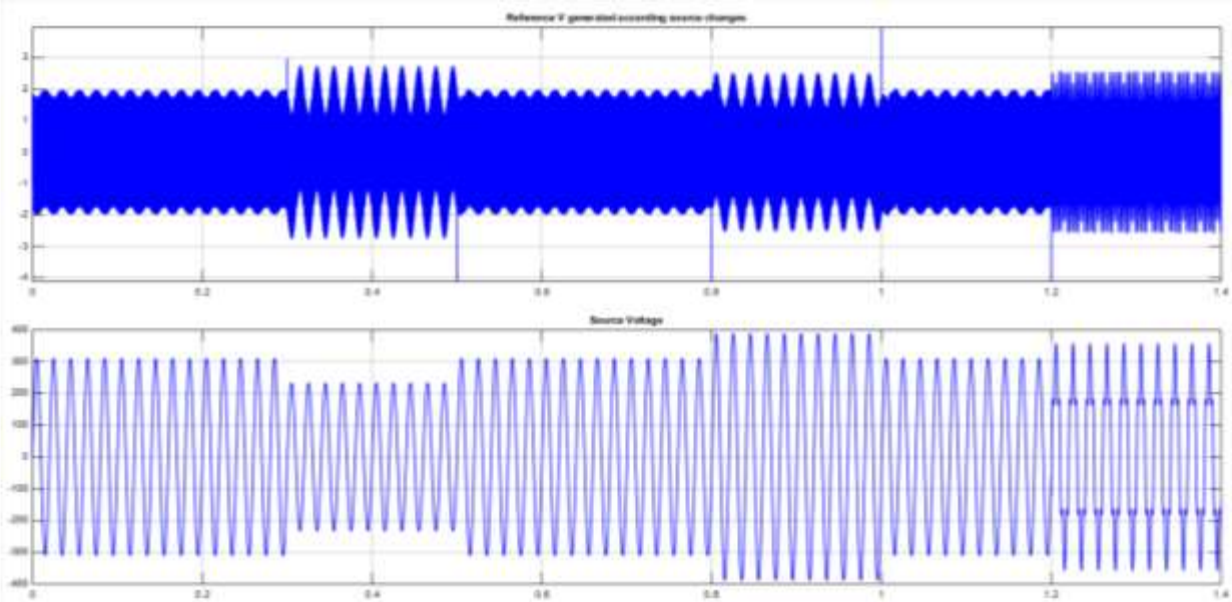

Fig-10: Reference voltage reference verses actual generation

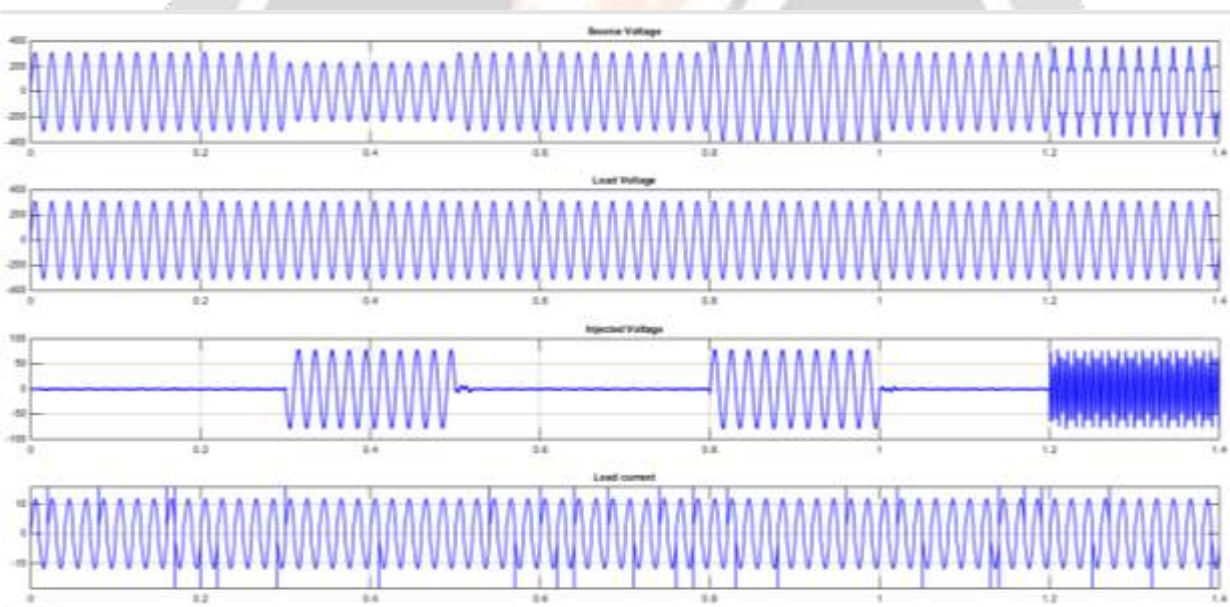

Fig-11: Simulation of the overall system with the THSeAF compensating current harmonics and voltage regulation. (a) Source voltage *vS*, (b) load voltage *vL*, (c) active-filter voltage *V*Comp, and (d) load current *iL*,

CONCLUSION

In this paper, a transformerless HSeAF for power quality improvement was developed. The paper highlighted the fact that, with the ever increase of nonlinear loads and higher exigency of the consumer for a reliable supply, concrete actions should be taken into consideration for future smart grids in order to smoothly integrate electric car battery chargers to the grid. The key novelty of the proposed solution is that the proposed configuration could improve the power quality of the system in a more general way by compensating a wide range of harmonics current, even though it can be seen that the THSeAF regulates and improves the PCC voltage. Connected to a renewable auxiliary source, the topology is able to counteract actively to the power flow in the system. This essential capability is required to ensure a consistent supply for critical loads. Behaving as high-harmonic impedance, it cleans the power system and ensures a unity PF. The theoretical modeling of the proposed configuration was investigated. The proposed transformerless configuration was simulated. It was demonstrated that this active compensator responds properly to source voltage variations by providing a constant and distortion-free supply at load terminals. Furthermore, it eliminates source harmonic currents and improves the power quality of the grid without the usual bulky and costly series transformer.

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