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Leakage current mitigation technique in solar PV system using passive filters

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KEYWORDS

Power flow, IEEE 14 bus system, Newton-Raphson, MALTAB, Photo Voltaic (PV), Renewable generation unit (RGU)

ABSTRACT

The parasitic capacitances in the transformer less solar photovoltaic (PV) array system develop the closed-loop path and generate the leakage current. As a result, it hampers the system performance with the presence of the leakage current such as electromagnetic interference, lessened the lifespan of PV panel, etc. To solve these issues, the passive filter is designed herein for the solar PV array system to suppress the leakage current. The frequency-domain analysis of the system is performed here in to carry out the optimum filter parameters. In this design approach, there is not any need for additional semiconductor switches, unlike the state-of-art systems. The adaptive controller is adopted herein to extract the fundamental component of the load current in order to provide effective harmonic compensation. Simulation results demonstrate that the presented passive filter effectively suppresses the leakage current within limits based on the DIN and NB/T grid codes. Additionally, several comparative analyses are performed to validate the practical feasibility and effectiveness of the presented system. The total harmonic distortions (THDs) of the grid currents are accomplished within 5% as per the revised IEEE standard 519 and IEC standard 61727.

INTRODUCTION

SOLAR energy conversion system (SECS) is the most popular among renewable energy sources due to having several advantages such as low maintenance costs, emissions-free, noise-free, etc. Due to technical advancements, the installation cost of the solar photovoltaic (PV) array system is significantly reduced. Panigrahi et al. have described the challenges of the grid-interfaced solar energy conversion systems, e.g., ride through operation, leakage current, inertia issue, inter- harmonic injection, synchronization, etc.

Many countries have revised the several grid codes to cope with these issues. Among those challenges, the leakage current is most prominent due to the existence of parasitic capacitances between the silicon layer and mechanical support, grounding surface, and protective glass.

The typical range of this parasitic capacitance is varied between 50 nF/kW to 150 nF/kW, which depends upon the type of silicon material used for the solar photovoltaic panel.

The transformer-based topologies provide galvanic isolation and nullifies the impact of these parasitic capacitances. However, this makes the system bulky, complex and also increases the cost of the overall system. Various single-phase topologies such as H5, H6, etc., are analyzed in the literature to maintain constant common mode voltage in order to lessen the high-frequency leakage current in solar energy conversion systems. However, these topologies require additional semiconductor devices and cause more losses and complexity in the system.

To address these issues, we have developed optimized H5 (oH5) and H-bridge zero-voltage state rectifier to suppress the leakage current in single- phase topologies. A detailed comparative analysis of various single-phase topologies is described in the literature.

However, the single-phase topologies suffer the double frequency power oscillations issue, thereby, the scholars have investigated the three-phase configurations to suppress the leakage current in the photovoltaic system. Several configurations such as H7 converter, H8 converter, modified H8 converter, H9 converter, etc., are described in the literature.

PROPOSED SYSTEM

In this project, the passive filter-based solar PV array system is presented herein to suppress the leakage current and obliges several grid codes. The detailed filter design procedure is discussed, and frequency domain analysis is performed to acquire the optimum selection of the filter parameters. In addition, the adaptive controller is incorporated herein for the smooth extraction of the fundamental components.

The adaptive controller has several advantages such as better convergence rate, good stability, low complexity, unlike traditional algorithms. The advantage of the presented solar energy conversion system is as follows.

- The passive filter design is proposed herein for a grid-tied solar PV array system to alleviate the leakage current without having any additional semiconductor devices. The detailed step-by-step design procedure is discussed to derive the filter parameters.
- Additionally, the frequency domain analysis is also demonstrated to illustrate the impact of variation in the filter parameters.
- Optimal parameters are chosen to suffice the objective of the leakage current alleviation.
- The adaptive controller is incorporated herein to extract the fundamental component of the load current in order to provide harmonic compensation.
- The stability analysis of the controller is also studied to analyze its performance for solar energy conversion systems.
- In contrast with the state-of-art systems the total harmonic distortions (THDs) of the grid currents are attained within the permissible limits enabling the balanced grid currents even under unbalanced nonlinear loads and adheres to the IEEE std. 519 and IEEE std. 61727.
- The presented system simultaneously follows the mandate revised IEEE std. 519, IEC std. 61727, DIN std. VDE-00126-1-1,

and NB/T std. 320004 even under coupled nonlinear load.

- Real-time hardware-in-loop performance is demonstrated to validate the effectiveness of the presented system.
- It provides satisfactory performance under manifold events such as load unbalancing, variation in solar insolation, distribution

static compensator (DSTATCOM) mode, and abnormal grid scenarios.

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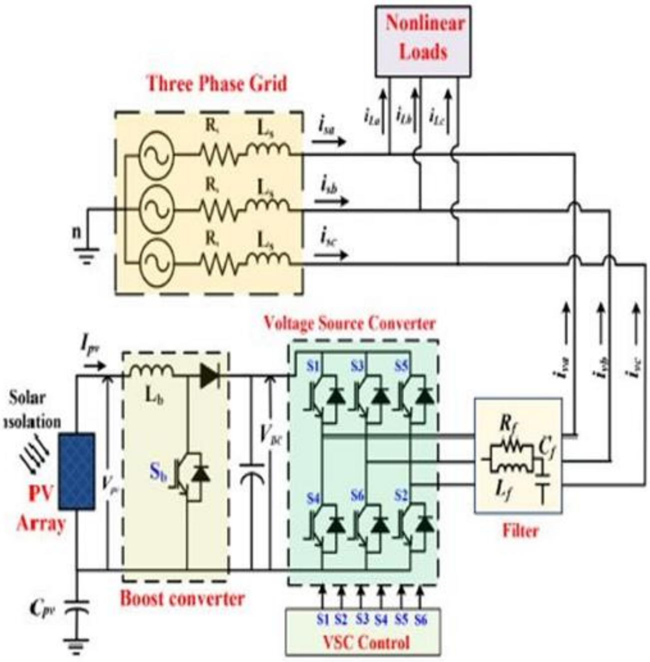


Fig: Schematic of three-phase grid -tied solar energy conversion system

It can be observed that the magnitude of the impedance offered by the system is substantially low for resonance frequency as depicted in Fig. 3.3. Hence, it offers a lower impedance path and permits the leakage current in the circuit. Therefore, the passive filter should be designed in such a way that it increases the impedance at the resonance frequency and enhances the system performance as depicted in Fig. 3.3 and Fig. 3.1shows the schematic diagram of the presented passive filter. The passive filter is coupled with the voltage source converter in order to suppress the switching voltage harmonics and current harmonics.

In addition, it provides a higher impedance path at the resonance frequency in order to suppress the leakage current. The presented filter consists of the parallel and series combination of resistor (Rf), inductor (Lf), and capacitor (Cf), which can be expressed using the second-order transfer

function. The input impedance (Zin) of the filter is expressed as,

$$Z_{in} = \frac{sR_f L_f}{R_f + sL_f} + \frac{1}{sC_f} \qquad (1)$$

Eq.1 can be expressed by rearranging the several terms as,

$$Z_{in} = \frac{\frac{s^2}{1/L_f C_f} + \frac{s}{R_f/L_f} + 1}{(sC_f)\left(1 + \frac{s}{R_f/L_f}\right)} \qquad (2)$$

From Eq.2, the detailed location of poles and zeros are described

The damping ratio can be expressed as,

$$2\delta\,\omega_2 = \frac{1}{R_f C_f} \Rightarrow \delta = \frac{\omega_2}{2\omega_1} = \frac{1}{2R_f}\sqrt{\frac{L_f}{C_f}} \qquad (3)$$

The damping ratio plays an important role during the transition at the corner frequency. To suppress the resonance frequency, corner frequency (ω2) of zero should be less than the resonance frequency of the grid (fgrid). If the damping ratio is chosen 0.5 then impedance offered at corner frequency between low-frequency asymptote and high-frequency asymptote is optimum.

If the damping ratio is less than 0.1 then the low impedance notch can be observed at corner frequency during the transition between low- frequency asymptote and high-frequency asymptote. If the damping ratio is more than 0.5 then the transition of impedance offered at corner frequency is high as compared to other cases. However, the impedance offered at high- frequency asymptote is also an important factor, which can be understood through three distinct cases. It can be explained as follows.

CASE-I: Let's consider, damping ratio (δ) = 0.5 and calculated the filter parameters are 251.32 Ω, 8 mH, and 126.65 nF, respectively. The bode plot for this designed filter is illustrated in Fig. 3(a). One can analyze that the designed filter provides significantly low impedance at high-frequency asymptote. Thereby, it permits the injection of the higher frequency components into the grid side network. Fig. 3(b) shows the frequency domain analysis with the integration of filter with solar energy conversion system. The offered impedance at higher frequency asymptote is quite low and it may hamper the system performance.

CASE-II: Let's consider, damping ratio (δ) = 1.5, the filter resistance, filter inductance, and filter capacitance are obtained using (2) and (3) as 83.77 Ω, 8 mH, and 126.65 nF, respectively. The frequency-domain bode plot for this designed filter and the overall system is illustrated in Fig. 3(a) and (b), respectively. Nonetheless, the improvement of impedance offered at high frequency asymptote is relatively low as compared to case-I. Therefore, the typical value of leakage current is significantly high as compared to case-I.

CASE-III: Let’s consider, damping ratio (δ) = 0.1 and designed filter resistance, filter inductance, and filter capacitance are 1.25 kΩ, 8 mH, and 126.65 nF. The frequency-domain plot for this designed filter is plotted in Fig. 3(a). It shows an excellent response as it effectively eliminates the resonance component from the grid and offers better impedance for resonance frequency. In addition, the frequency domain plot with the integration of this designed filter with an overall system is demonstrated in Fig. 3(b). One can observe that it offers a better impedance trajectory at high-frequency asymptote as compared to case- I and case-II. Hence, these filter parameters are chosen for the satisfactory performance of the grid- tied solar PV array systems.

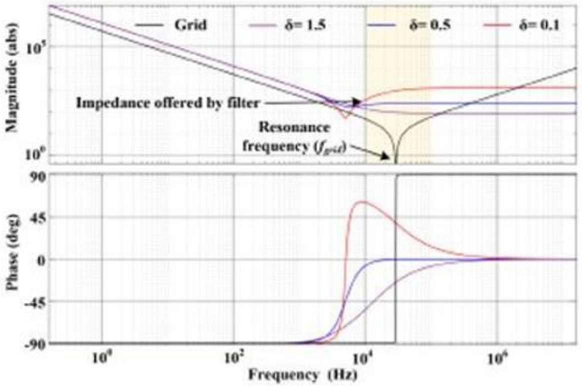


Fig.3.4: frequency domain analysis of only filter

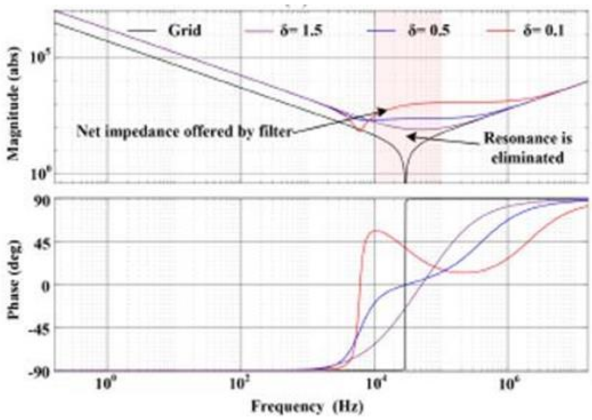


Fig.3.5: frequency domain analysis of filter and coupled solar energy conversion system

RESULTS

a) Simulation results of Start-Up dynamics of SECs

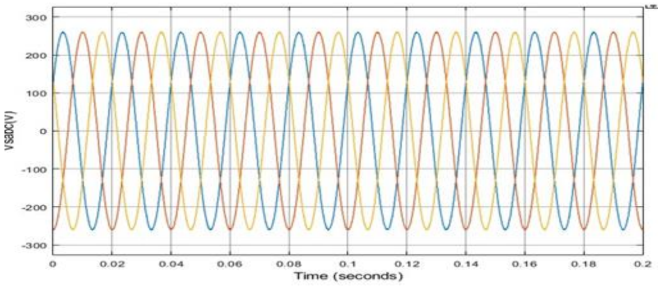


Fig: Grid voltages are constant

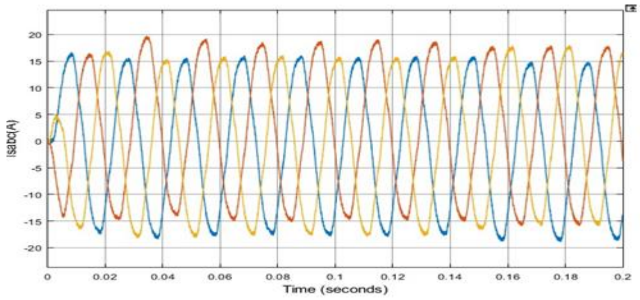


Fig: Grid currents are smoothly increased

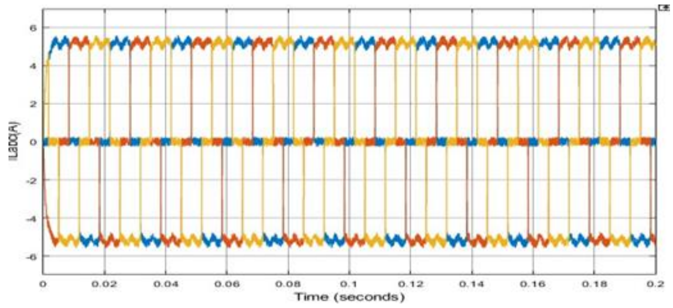


Fig: Non-Linear characteristics of local load

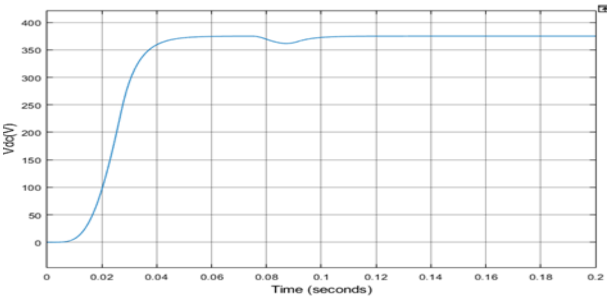


Fig: RMS value of the leakage current is Sustained within limits

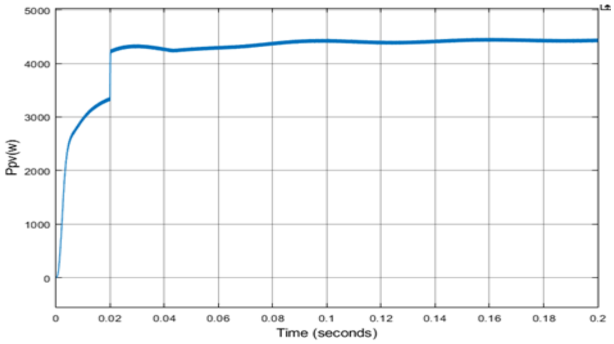


Fig: DC bus voltage is regulated as per reference value

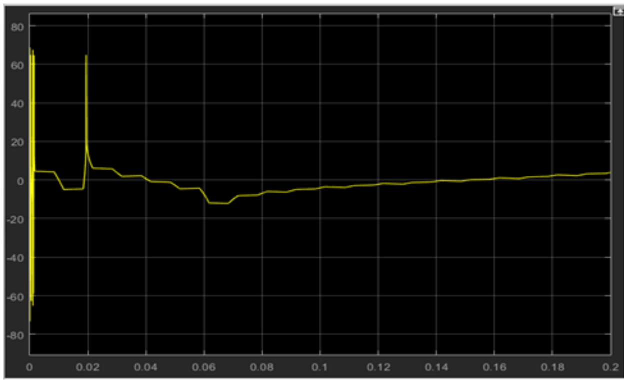


Fig: Boost Converter extract maximum power

b) Simulation Results of a Behaviour of system under Load Un-Balancing scenario

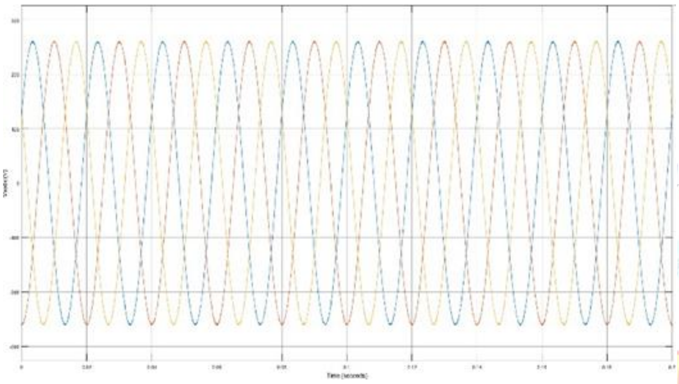
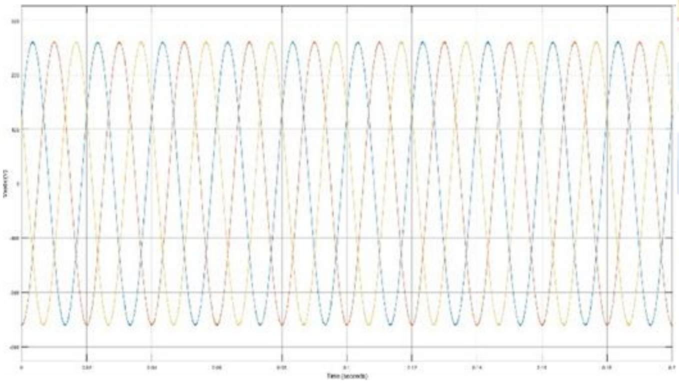


Fig: Balanced and sinusoidal grid voltages



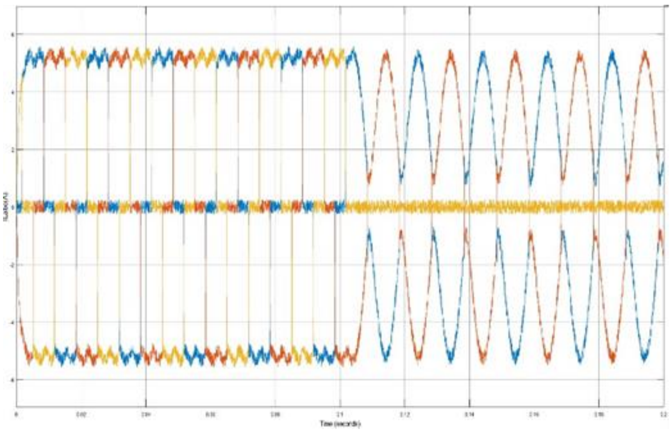


Fig: unbalanced loading scenario

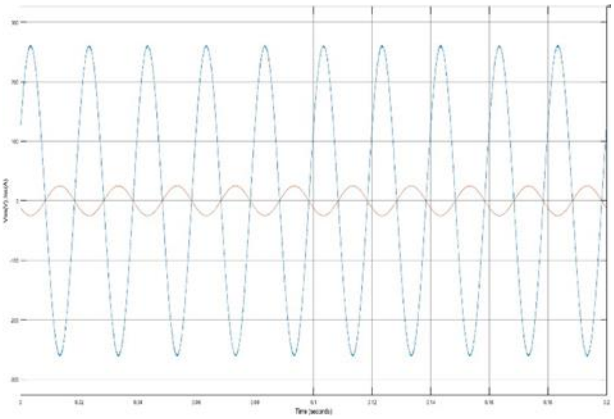


Fig: Unity Power Factor Operation (Scaled Voltage)

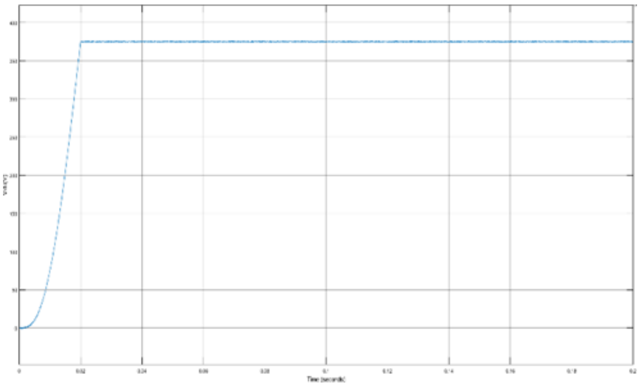


Fig: Dc voltage is effectively regulated

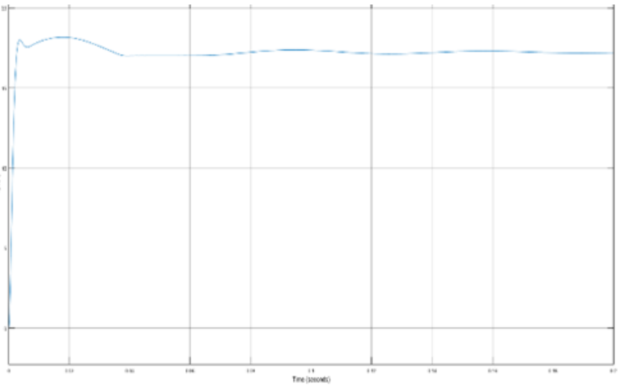
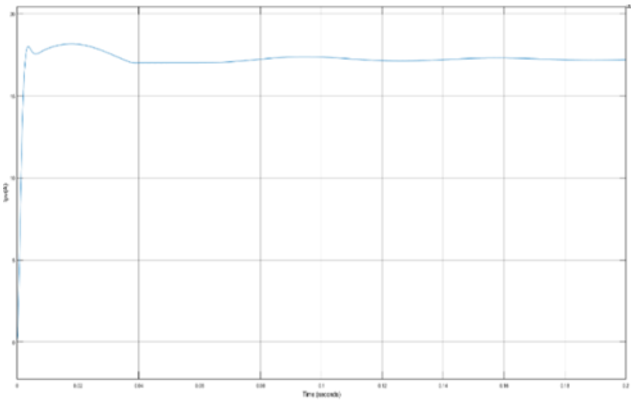


Fig: Solar power generation is not affected



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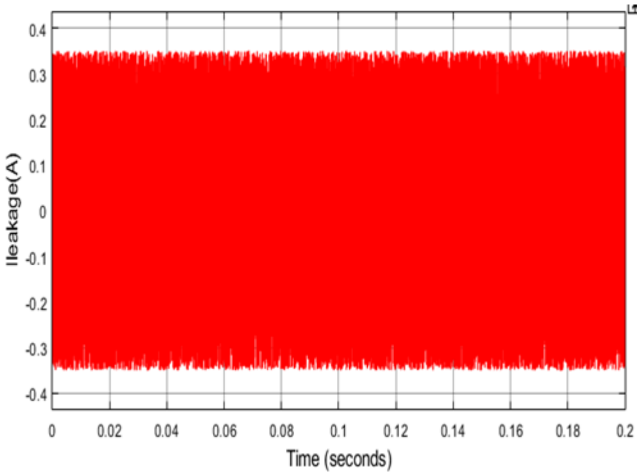

Fig: Leakage current is supressed within limits

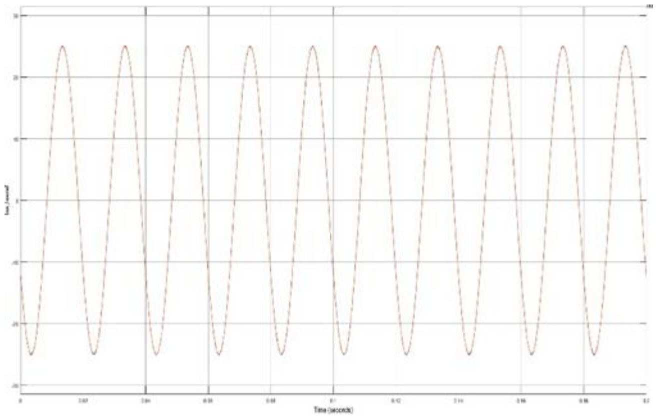

Fig.4.2(j): Current controller effectively tracks reference current

c) Simulation Results of Performance of a system with variation of solar Insolation

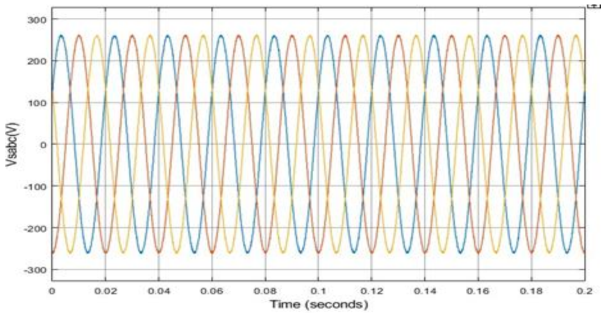

Fig: Three-phase grid voltage waveforms under varying solar insulation conditions

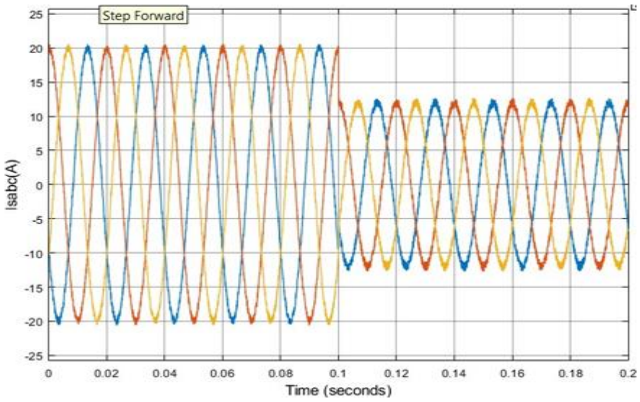

Fig: Impact of solar power generation is reflected to grid

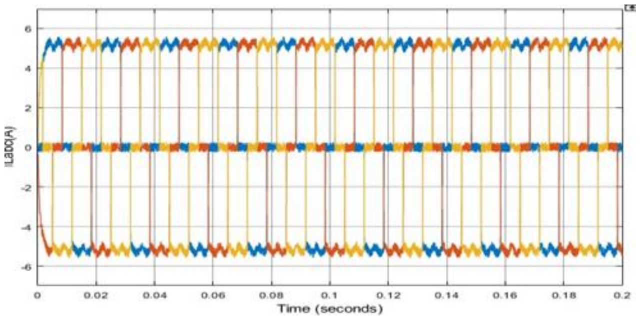

Fig: constant impedance load

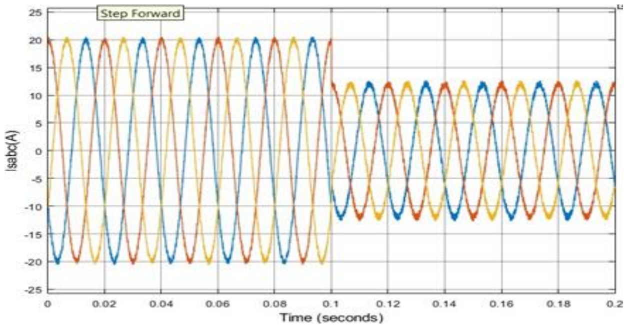

Fig: Injected converter currents

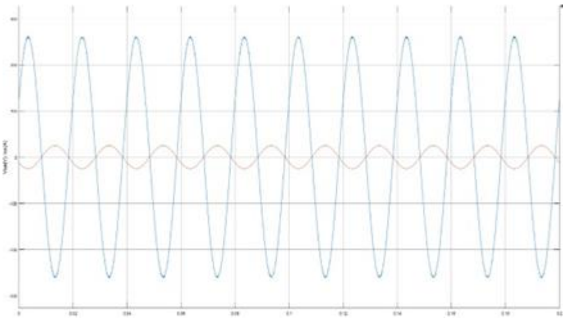

Fig: Unity power factor operation (scaled voltages)

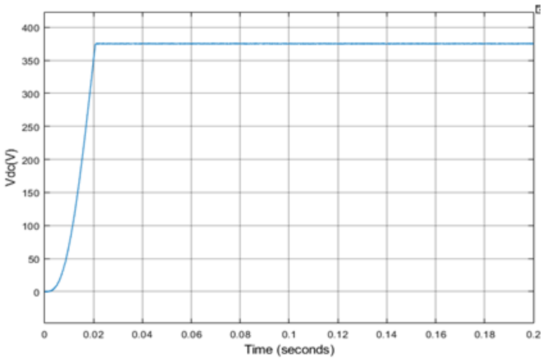

Fig.4.3(f): DC voltage rising quickly and steady- state stabilizing

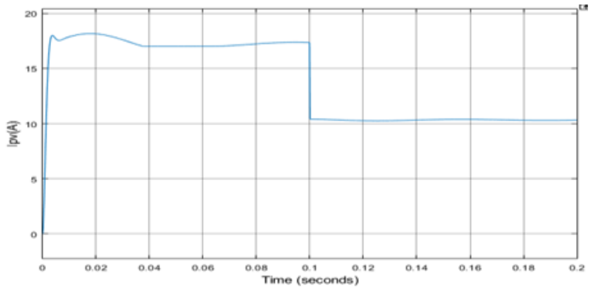

Fig.4.3(g): Change in solar power generation

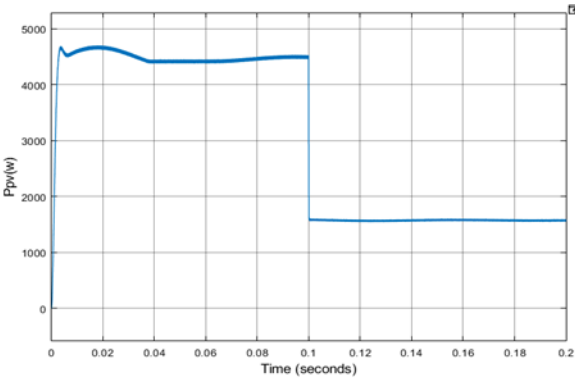

Fig: Solar power generation is varied based on insolation

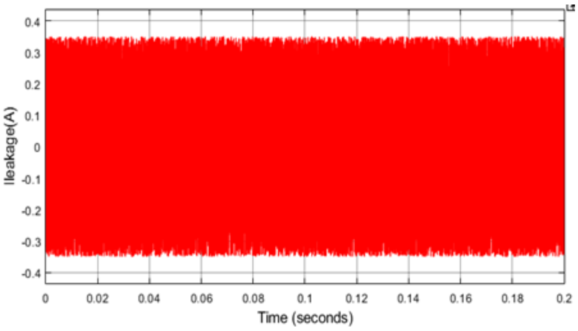

Fig: Leakage current is attained within limits

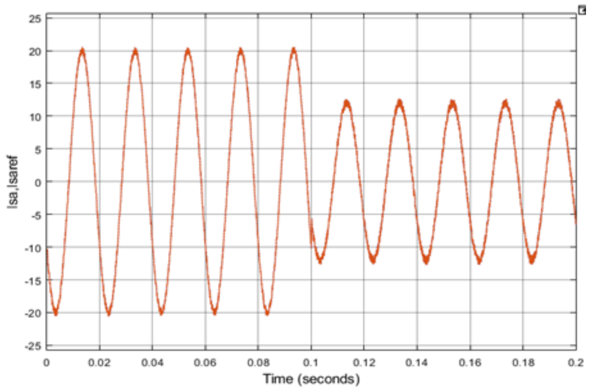

Fig: Tracking performance of hysteresis current controller

CONCLUSION

The passive filter design is presented for solar PV array systems to alleviate the leakage current enabling power quality improvement features. The novel passive filter design technique is studied and analyzed the dynamics under various operating scenarios. The distinct advantages of the presented work are summarized as follows.

(1) The novel passive filter design has been presented to suppress the leakage current and improves the system dynamics even under wide variation of the solar power generation;

(2) The leakage current is restricted in the range of 195 mA as per the prescribed limits of DIN standard VDE- 00126-1-1 and NB/T standard 32004, without any additional semiconductor devices or topology reconfiguration, unlike state of- art systems,

(3) The balanced and sinusoidal grid currents are attained even under unbalanced load currents and its THD values are also accomplished in the range of 2.5% as per the recommended IEEE standard 519 and IEC standard 61727; and

(4) The adaptive controller effectively compensate the harmonics and provides robust operation even under abnormal grid scenarios.

The stability and convergence analysis of the adaptive controller has been demonstrated to evince the robustness property and the boundedness of estimated harmonic components, respectively. Simulation results demonstrate satisfactory performances under various dynamic operating scenarios. Comparative leakage current analysis and THD performance versus the variation in solar power generation have been carried out to ensure the efficacy of the presented work over the state-of-art strategies.

In real-time, the practical power grid is subjected to continuous variation in system parameters, and the presented approach is served as a possible solution to provide better performances owing to its self-adaptation to the changes in the environment. There by, the real-time hardwareinloop model is validated for a three-phase gridconnected solar energy conversion system and illustrates the excellent response under district operating scenarios.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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