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Improved Voltage and Frequency Control in Smart Grid using a Novel Customized Active Power Control with Smart PV Systems

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Abstract— During present days, the grid systems play an important role in generating self-sufficient power for customers from service providers. Moreover, the advantages of grid such as low cost, stability and wide area coverage, specifically in smart grids make its usage in a wide range. Generally, smart grid system provides self-healing abilities and allows electricity users as active participants. However, the challenges in smart grids like contingency, flexibility, reliability, and security issues still exist. This research introduces a novel approach for achieving the adaptability of smart grids with the intelligent solar photovoltaic (SPV) systems. The proposed model used Customized Active Power Control (APC) for improving the operation of SGs having minimal voltage deviations and frequency variations. The attained results demonstrate the enhanced voltage and frequency control in varying parameters such as voltage, frequency, curtailment, and de-curtailment with respect to active and reactive powers.

Keywords: Active Power Control, Smart SPV System, Smart Grid, V-w Control, and f-w Control.

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Introduction:

Because of rise in the concerns towards the environmental issues makes the researchers to investigate novel methodologies based on Distributed Generation (DG) with renewable using grid systems [7]. Typically, grid functions as a self-sufficient power source with the integration of Energy Storage Systems (ESS), DG, and various load levels [9]. A grid is a one-way interaction among supplier and the consumer. Conversely, a smart grid allows two-way communication in a digital format such as data as well as electricity between the provider and the multiple users. For this reason, implementing smart grids enables several advantages over traditional grids. A smart grid includes tens of thousands of pieces such as system controls, computers, power lines, and numerous equipment and methodologies. With the large pack of equipment and machinery components and new technologies, a smart grid requires some time to get installed, system to be verified and checked before implementation. Although, some processes are time consuming, a smart grid enables simple integration with huge penetration of renewable powers. Furthermore, it is necessary to improve the progress and extensive implementation Hybrid Electrical Vehicles that Plug-in. Thus, PHEVs can be employed as storage for grid systems. However, a smart grid structure is still limited by the issues in implementing a completely reliable, interoperable, and fully stable electrical energy. Moreover, time synchronization, complication in information deliverance and latency restricts the performance of fully secured and controlled smart grid infrastructures. In order to overcome the limitations, repeated communications and complicated computation are eliminated [10]. In the recent days, several distribution systems undergo a considerable DG penetration, PE-converters with high loads,

complicated EV-charging, several narrow storage choices, and customer flexibility issues lead to various complexities.

Occasionally, the communication is to be but not from the source grid in some places. With the intension of improving voltage and frequency control in smart systems, APC with smart PV systems is introduced in this paper. Generally, voltage and frequency play a major role in smart grids to provide real as well as reactive power balances for a stable power supply. Here, voltage control is considerable to maintain stable, reliable and secured electricity for both providers and customers. Similarly, frequency control is important as it provides the balance among production and utility. Moreover, it needs proper knowledge about the security constraints to function properly otherwise, the entire grid becomes unstable. Thus, it is significant to maintain a perfect V-F control in smart grids to attain improved and stable production and consumption. With the intension of improving V-F control in smart grids, a novel APC method is implemented using smart PV systems in this paper. This work primarily focuses as follows:

- An improved voltage and frequency control method is implemented using Customized APC with smart PV systems.
- The proposed work minimized the voltage fluctuations and frequency deviations and thus provides enhanced voltage profiles with high performance.
- The simulation outcomes demonstrate the suggested smart grid (SG) model's adaptability and effectiveness in relation to voltage, frequency, active & reactive powers.
- In future, complexities in implementation will be reduced by applying optimization and deep learning methods to attain optimized control in smart grids.

I. Literature Survey:

A. Relevant Work

Shan et al. [1] in 2020 has developed a system that used a Model Predictive Power Control model to select and building up a DC-DC converter as well as with grid-interconnected PV inverter for ESS. With the assistance of MPPC, the p. f. was enhanced along with achieving voltage & frequency stability in the power grid through controlling dc-bus voltage via managing active and reactive power supply. Experimental outcome proved the efficacy of this work via numerical evaluation with the Controller Hardware-In-the-Loop (CHIL) methods.

In 2020, Howlader et al. [2] have implemented a real-time model which evaluated the performance of smart grid to eliminate potential fluctuations with frequency changes using smart PV inverters. For this implementation, v-w, f-w along power curtailment schemes were used. Moreover, Power curtailments methods were analyzed with high as well as low PV penetration places. Investigational evaluations were done at Maui Smart Grid project, Hawaii.

In 2020, Giacomuzzi et al. [3] have proposed a model that used a medium voltage smart transformer grid system through ST-LV with APC. This work achieved enhanced voltage profiles with minimized time limits. It was analyzed through two effects such as minimized active power

consumption in MV grids and enhanced voltage support. The experimental outcomes demonstrated the performance via various voltage dependent loads at low-voltage grid.

In 2020, H. Almasalma and G. Deconinck [4] have introduced a system that used a control model to Photovoltaic (PV) battery systems for maintaining concurrent distributed voltage control as well as frequency containment reserve. It included day-ahead & real-time two stages. In former stage, optimized frequency control was achieved and in later stage, enhanced voltage control was attained. From the experimental results, the proposed model achieved better performance and robustness.

In 2020, Khan et al. [5] have discussed a model which used a smart low voltage ride-through (LVRT) controller. Here, the characteristics of electricity supply to voltage support from SPVs and synchronized functions of MPPT as well as ride-through controller throughout grid irregularity for longer period were presented. The simulation outcomes analyzed the efficiency of several grid systems with respect to reliability and stability.

In 2015, Bayat et al. [6] has developed a system that used a unified control model to enable REDs (Responsive End-user Devices) like PHEVs, PVs and enhanced voltage & frequency control in smart grids. Here, the implementation was done on different buses. The voltage control was implemented via two groups like, active support group & reactive support group. Furthermore, frequency control was implemented with one active support group. Whole complexity in the system was solved using Particle Swarm Optimization (PSO). The simulation's outcome verified the efficiency of the optimized model in relation to enhanced voltage and frequency control and security.

B. Review

There are numerous methodologies and technologies have been implemented for enhancing the voltage profiles with frequency controls of smart grids for attaining stable and reliable power. However, the complexities in smart grid like, unexpected voltage fluctuation & frequency deviations limit the performance and reliability of entire grid system. Model Predictive Power Control method [1] model attained enhanced control over voltage yet the model lacks performance and the implementation were time consuming. The real-time smart grid [2] evaluation discussed the complexities in grid system both the voltage and frequency controls. The ST-MV [3] model achieved minimized active power consumption and enhanced voltage profiles still the complexity exists in terms of implementation cost and security. The PV-battery model [4] attained minimized cost and better profits but it was a time-consuming process in real-time implementation. The LV-RT controller [5] achieved stability and reliability yet under various grid systems, the performance was limited due to implementation complexities. Although, the unified control model [6] accomplished efficient voltage and frequency profiles, the performance depends on the selection of appropriate bus system. A wrong selection causes implementation failure and loss of profits. Thus, there is a strong recommendation to develop novel and efficient voltage and frequency control model to SG related to reliability, stability, low cost & its security.

II. A Novel Smart Grid Model with Active Power Control:

A. Proposed Architecture

This part contains the explanation on proposed model of Customized APC. Here, fig.1below depicts the conceptual image of the proposed smart grid system. Here, the renewable power sources such as

solar PV arrays, wind mill, tidal and thermal powers are connected to the smart PV inverter (here solar PV arrays are used). Generally, the PV arrays generate DC volt current which necessitates the implementation of an inverter to convert the DC current to AC current. For this purpose, a smart PV inverter is employed which includes voltage and frequency controlling strategy via proposed Customized APC model. From the inverter, the generated current is fed to service transformer which supplies electricity to household, distribution lines, vehicle charging, etc. Here, a network is employed to collect the data from the service transformer which is then used to regulate and maintaining the stability along with flexibility for smart grid system. Through the wireless communication devices, the data are collected from the transformers to the network by the servers which can be accessed via the computers.

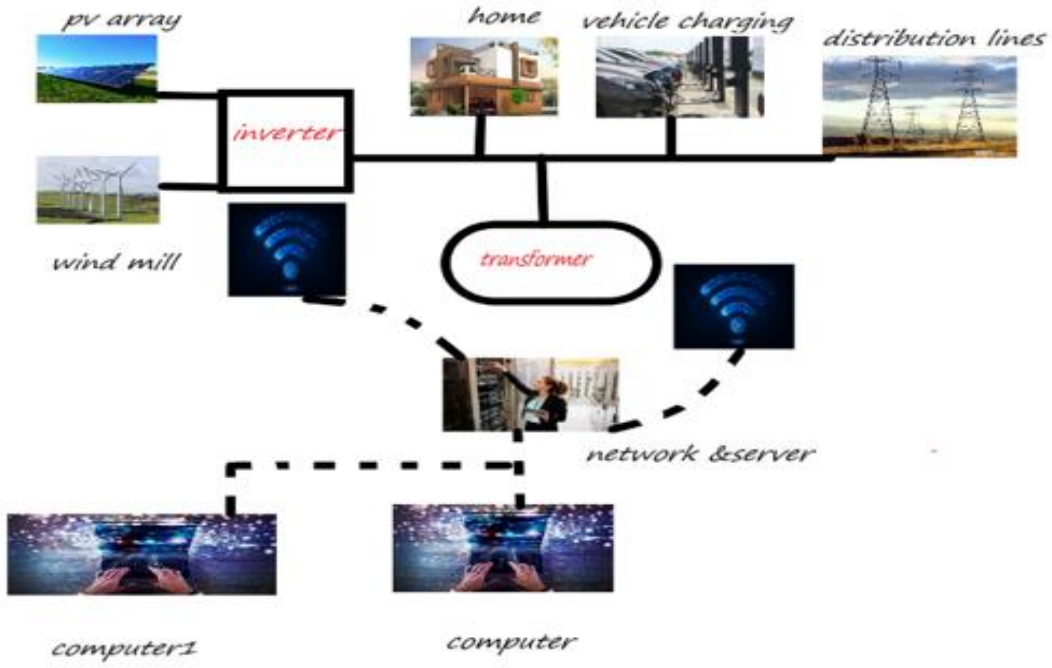


Fig. 1. Schematic Representation of Proposed Smart Grid System

Thus, an enhanced smart grid system to provide better electric power by means of regulated voltage and frequency profiles to the consumers are implemented. Moreover, Fig. 2 shows the implementation of proposed Customized APC model in the smart PV inverter. Initially, a DG SPV panel is attached through smart photo voltaic systems to the grid. With the help of smart PV inverters, advanced managing features such as real power curtailment, stable p. f. control, v-w control, as well as f-w control can be employed. Furthermore, a DC-DC boost converter is implemented with a solar PV panel, MPPT and a grid connected inverter.

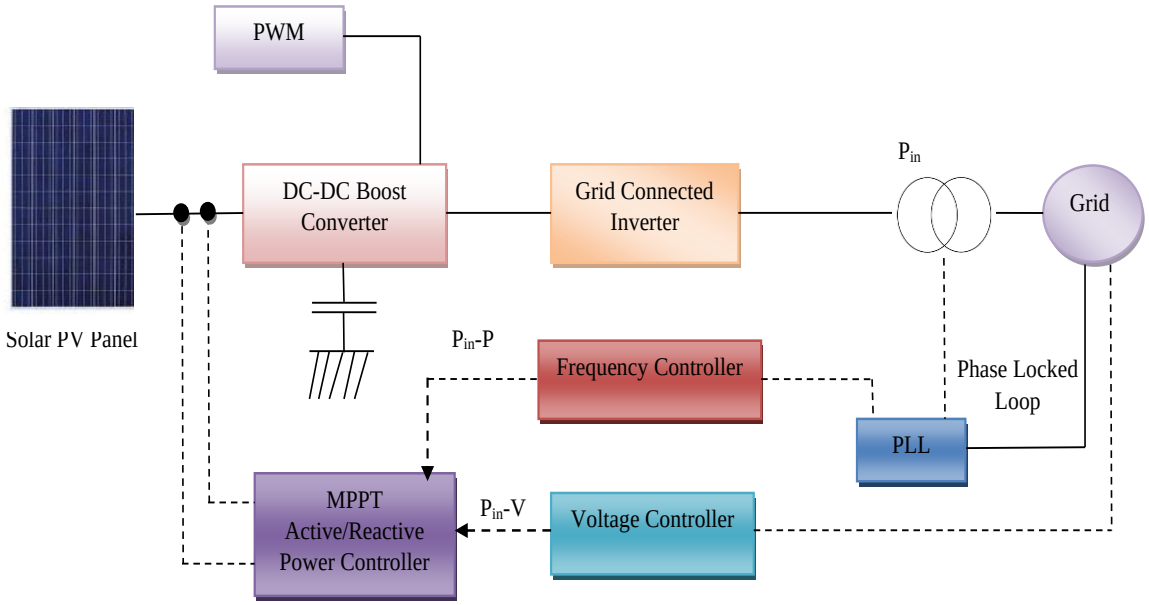


Fig 2. Systematic Implementation of Proposed Customized APC model in Smart PV Inverter.

III. Component Models:

A. SPV System model

Here, Fig. 2 illustrates the single line model of PV implementation. According to this model, when the solar energy (irradiance) hits on the panels, it produces solar power (electricity). Generally, solar energy varies due to various climatic conditions and periods every so often. This leads to deviations of generated PV system voltage level. To stabilizing the voltage changes, voltage obtained from the SPV panel is changed via dc-dc boost converter to fixed range. Moreover, dc-dc converter confirms the MPPT control and APC that is frequency & voltage control with the active power curtailment in PV system. Here, the notations V_{pk} and i_{pk} indicate voltage and current outcomes from the PV system which are applied as inputs for MMPT/APC controller for controlling the MPPT block. The PLL block gets the grid voltage V_{gv} as the input for controlling the frequency F^k, as well as the phase angle, θ^k. Furthermore, the f-w control curve gets the frequency, F^k as intake which is employed for controlling the APC command, P*in_fw. Similarly, the v-w control curve gets grid voltage V_{gv} as input which provides the APC command, P*in_vw. In addition to this, P*in_cur denotes the active power curtailment control along with the APC commands P*in_fw and P*in_vw are given as inputs to the MPPT/APC block which controls the active power outcomes from the PV panel. Herein, a three sets of input controls are provided externally to the MPPT/APC block that is true power curtailment Pin*_cur, v-w Pi*n_vw, & f-w P*in_fw controls respectively. Furthermore, the dc-dc inverter in Fig. 2 is employed for supplying active power outcomes for electric grid from SPV panels. Here, the active power outcome determines the amount of electricity developed from SPV systems.

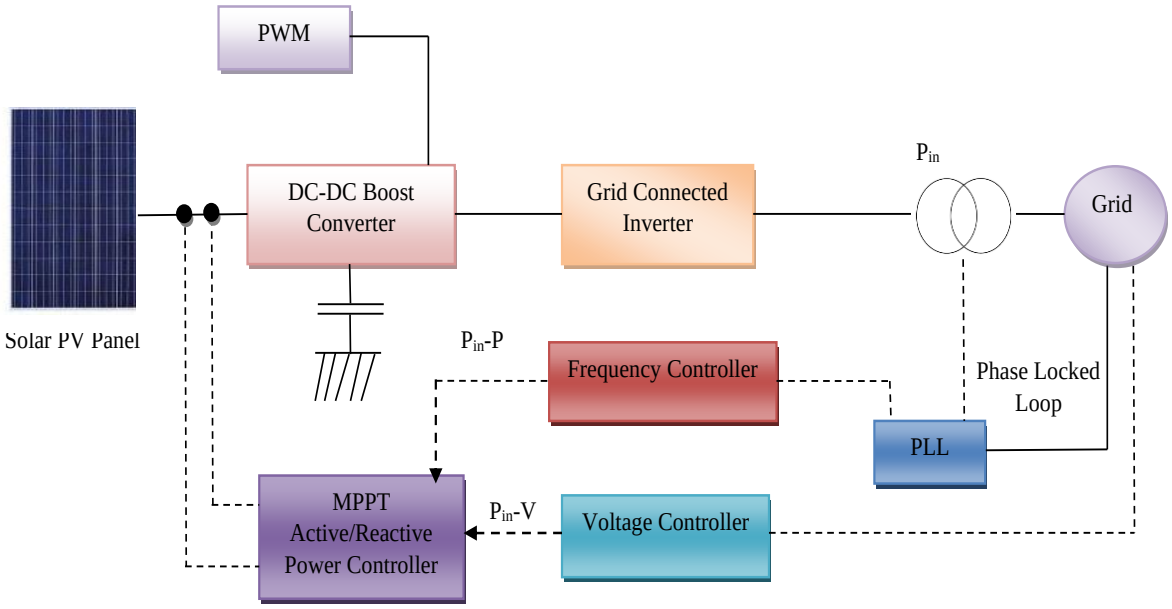
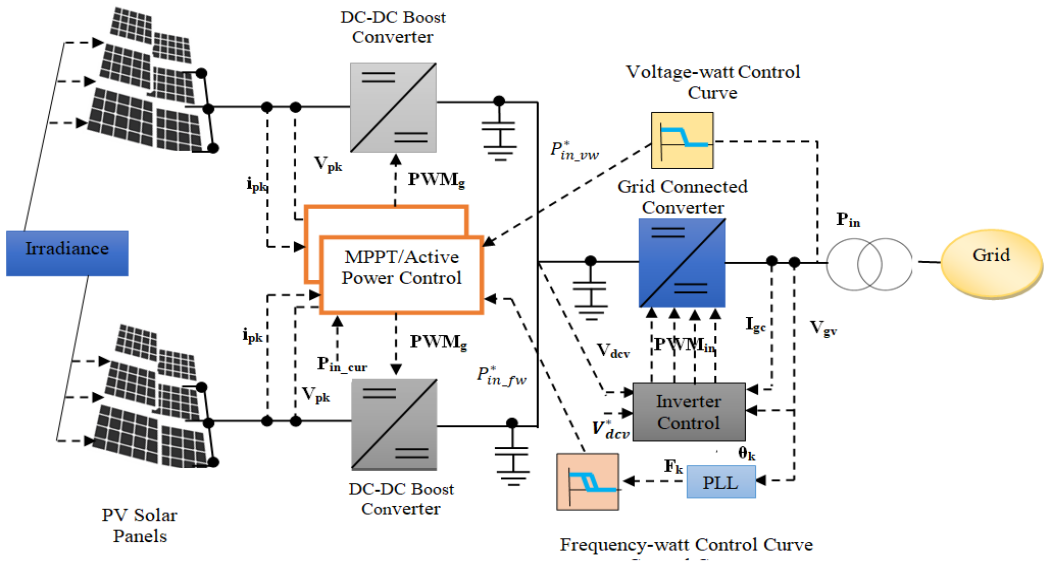


Fig. 2 Systematic Implementation of Proposed Customized APC model in Smart PV Inverter.

The DC link voltage, V_{dcv} along with grid voltage, V_{gv} are managed by inverter control system. Besides, Fig. 3 depicts the PV power model of MPPT/proposed customized APC model. Here the voltage controller employs the v-w control function with frequency curve uses f-w control curve.



PV Power Model with MPPT/ Customized APC Model.

Addition to this, Fig. 4 below portrays the flow chart of the proposed smart grid (SG) system.

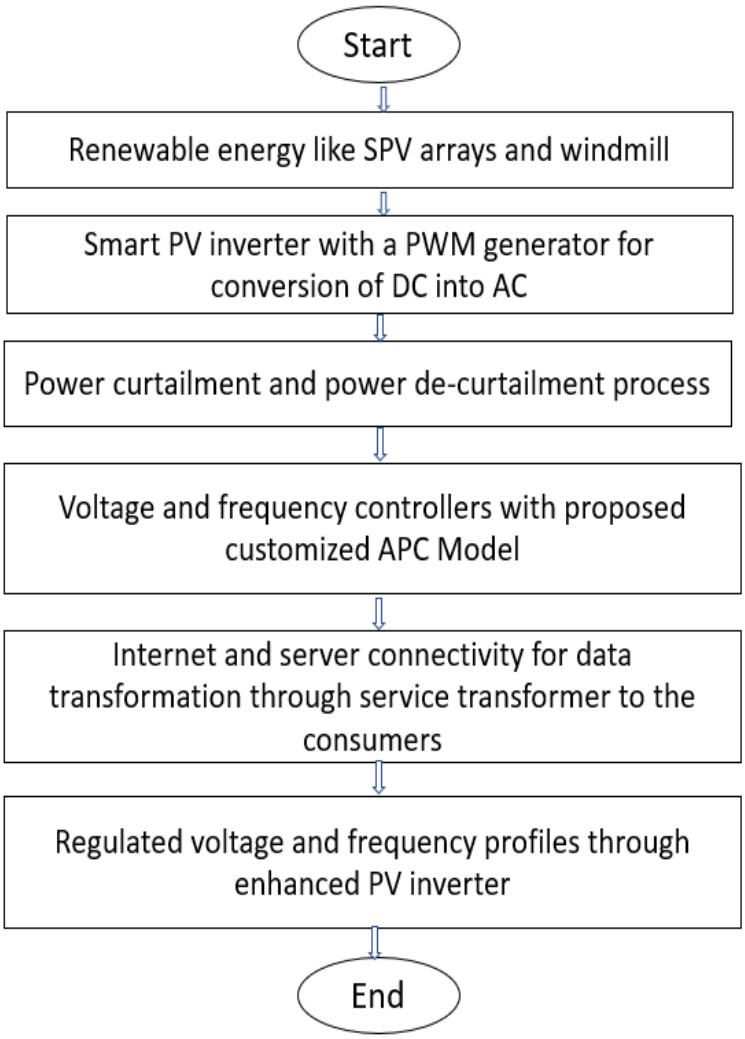


Fig. 4 Flow chart of Proposed Customized APC Model in SG System

B. Boost Converter Control Model

In this subsection, the boost converter control model in MPPT/APC system is presented. Based on the converter control model, the initial PV power outcomes are evaluated as given in Eq. (1), in which P_{out} (T) indicates the instant PV power outcome through DC-DC boost converters. Besides, P_{out} (T) is given as the inputs to the inverter.

$$P_{outs}(T) = \begin{cases} P_{pk}(T) \\ P_{in_{cur}}(T) \\ P_{in_{fw}}(T) \\ P_{in\_vw}(T) \end{cases} \quad \text{---------- (1)}$$

Here in, P_{pk} (T) indicates determined power outcome of SPV system after performing maximum power point tracking (MPPT) control commands. Besides, Pin_cur (T), Pin_fw (T), & P*in_vw (T) point out the outcomes of the SPV system after performing the power curtailment command, f-w control & v-w control respectively. MPPT/APC block produces the voltage command V*pk as well as the error signal from the SPV systems that act as input signals to the PI controller to send the MPPT control signal for the dc-dc boost converter system. Furthermore, fix-watt curtailment control

is sent for converters via proportional integral (PI) controller which gets input from the error signal among true SPV power outcome P_{pk} with constant power curtailment control P*pk through the fix-watt curtailment command. Also, v-w control curve gets input from the grid voltage V_{gv} for v-w control model. Moreover, the v-w control curve is evaluated to determine actual power curtailment from smart SPV system by means of response from the terminal voltages.

Here the voltage and frequency controls are implemented as separating three regions with four groups of voltage points like V^1, V^2, V^3 & V^4. Region-I represents 100 percent available power production and region-II denotes variable watt production. In order to avoid sleep mode functions of the inverters, the smart PV system disallow power curtailment until it reaches 100%. Thus, Region-3 denotes 90% power curtailment area. Voltage, V_{gv} and voltage points V^1, V^2, V^3 & V^4 and are given as the inputs to the volt-watt control model and the APC command $P^*_{in\_vw}$ of the converter is evaluated as 10% to 100% for the PV inverter as stated in Eq. (2).

$$P^*_{in\_vw} = \begin{cases} 100\%, & if\ V^1 \le V_{gv} \le V^2 \\ 10\% - 100\%, & if\ V^2 \le V_{gv} \le V^3 \\ 10\%, & if\ V^3 \le V_{gv} \le V^4 \end{cases} \quad \text{---------- (2)}$$

As mentioned above, the converter's volt-watt control signals are produced from the PI controller which gets input from the error signals generated from the APC command $P^*_{in\_vw}$ as well as the actual PV power P_{pk}.

On the other hand, the f-w control curve gets input signals from grid frequency F^k to f-w control block. Besides f-w control model describes the functions of actual power curtailment & de-curtailment by means of responses from the terminal frequency in the smart PV panels. The curtailment & the de-curtailment of smart SPV inverter is based on the frequency control command. Usually, it is a vice versa process as the frequency increases, the curtailment process of smart PV systems takes place. Conversely, as the frequency decreases, the de-curtailment process of smart PV systems takes place. Here, the frequency-watt control is depicted as seven group of frequencies like F^1, F^2, F^3, F^4, F^5, F^6 & F^7. Now, eq. (3) shows the APC command P*in_vw for the increasing frequency input, of f-w control curve.

$$P^*_{in\_fw} = \begin{cases} 100\%, & if\ F^1 \le F^k \le F^2 \\ 10\% - 100\%, & if\ F^2 \le F^k \le F^3 \\ 10\%, & if\ F^3 \le F^k \le F^4 \end{cases} \quad \text{---------- (3)}$$

To the contrast, Eq. (4) defines the APC command P*in_fw for the decreasing frequency input, P*in_fw control curve.

$$P^*_{in\_fw} = \begin{cases} 10\%, & if\ F^5 \le F^k \le F^4 \\ 10\% - 100\%, & if\ F^6 \le F^k \le F^5 \\ 100\%, & if\ F^7 \le F^k \le F^6 \end{cases} \quad \text{---------- (4)}$$

The PI controller gets the inputs from the variations among the APC command P*in_fw and the actual PV power command P_{pk} which produces the frequency-watt control command. The PI

controllers produce the DC-DC boost converter's PWM gate signal PWMg according to the type of APC commands such as P*in_fw and Pin*_vw.

C. Inverter Control Model

For the inverter control model, the PI controller gets inputs from the error among actual and reference DC link voltage, V*dcv for managing it. In addition to this proportional integral controller produces d-axis reference current, i^*_{dv}. Similarly actual grid voltage, V_{gv} as well as the reference grid voltage V^*_{gv} are employed to evaluate the q-axis reference current, i*qv. Here, I_{gc} indicates the grid current, i_{dv} and i_{qv} are dq-axis true currents, I_gc phase shift & the phase angle θ^k gets inputs through performing the Inverse Park Transformation. Moreover, the current controllers get the inputs from the error among the dq-axis actual currents such as i_{dv} and i_{qv} and the outputs from dq-axis reference voltages. Eventually, the pulses PWM_{in} for initiating the inverter gates are produced by the PWM generator.

D. Volt-watt (v-w) Control Model

Presented here a v-w control model in this part. Observing the consequences of the v-w control in smart SPV system, voltage points are employed from the v-w control curve. Once output voltage of inverter goes under range below voltage point V^3, then region-3 is activated and the inverter performs accordingly. This leads to the inverter to curtail the current until it reaches 10% of the rated power. With the intention of verifying the function of smart inverter, V^3 voltage point may be employed to obligate the inverter to perform under region-3 criteria. For a certain period of investigation of v-w control command, output terminal voltage of smart SPV system operates among voltage points V^3 and V^4 that indicates the region-3 with respect to the eq. (2). Consequently, actual power of inverter undergoes a curtailment of 10% rated power and results in decrease at output terminal voltage of smart SPV inverter (power curtailment takes place). Controversially, inverter terminal voltage raises owing to power de-curtailment process. This proves that the DG voltage of smart grid may be controlled through the v-w control model.

E. Frequency-watt (f-w) Control Model

This section evaluates the f-w control model. For this purpose, frequency points like F^1, F^2, F^3, F^4, F^5, F^6 & F^7 are employed. Generally, the frequency implemented in smart grids possess only a slight variation as it always sustains at a minimal value. Thus, the frequency point values are set closely together. This implementation uses the active power of smart SPV inverter that undergoes power curtailment of 10% rated power only if the frequency deviates over the frequency point F^3 value. Thus, actual power curtailment of smart SPV inverter minimizes the upward frequency. On the other hand, once the frequency level undergoes less than the frequency point, F^6, then the smart grid system gets 100% power generation from the inverter. Here, actual power curtailment & de-curtailment process regulates the frequency deviation and helps to attain 100% power generation by the inverter.

IV. Results of Simulation:

(a) Performance Analysis

This suggested smart grid model based on Customized APC model has been accomplished in MATLAB 2019a on Intel core i3 processor 7020U @ 2.3 Giga Hz, 8 Giga Byte Random Access

Memory, 64-bit OS. The outcomes of the simulation were used to track the effectiveness and uniqueness of the model that was put into use. In this case, the evaluation was carried out using a variety of performance metrics, including controls for voltage, frequency, active power, and reactive power.

(b) Performance Evaluation

Here in this part of discussion, experimental findings of suggested customized Active Power Control (APC) Model have been presented. In fig. 5 the power curtailment model of proposed method is depicted. Moreover, fig. 5 (a) shows the performance of actual power curtailment over time. Similarly, the performance of the suggested model in relation to reactive power curtailment is depicted in fig. 5 (b). The fig. 6 shows how the Customized APC's voltage & frequency may be controlled with the help of power curtailment procedure. In addition, figures 6 (a) and 6 (b) show the grid voltage, Vgv portrays the frequency F^k performance. Here, the frequency deviations are minimized with 1 second of time and the voltage stability is achieved from 60 volt to 50 volt within 1-second. Besides, fig. 7 depicts the overall grid voltage V_{gv} performance at power curtailment process. In addition to this, the power de-curtailment process is illustrated in fig. 8. The performance of active power de-curtailment is displayed in fig. 8(a) here over time. The proposed model's performance at reactive power de-curtailment is also shown in fig. 8 (b). Voltage (V) & frequency (f) control of customized APC through power de-curtailment process was demonstrated in fig. 9. Furthermore, fig. 9 (a) depicts the grid potential V_{gv} & fig. 9 (b) portrays the frequency F^k performance. Here, the frequency deviations are minimized with 1 second of time and the voltage stability is achieved from 60 volt to 50 volt within 4 seconds. Thus, the proposed Customized APC model proved its efficiency and attains regulated voltage and frequency effectively. Besides, fig. 10 depicts the overall grid voltage V_{gv} performance at power de-curtailment process. Thus, the proposed Customized APC model proved its efficiency and attains regulated voltage and frequency effectively.

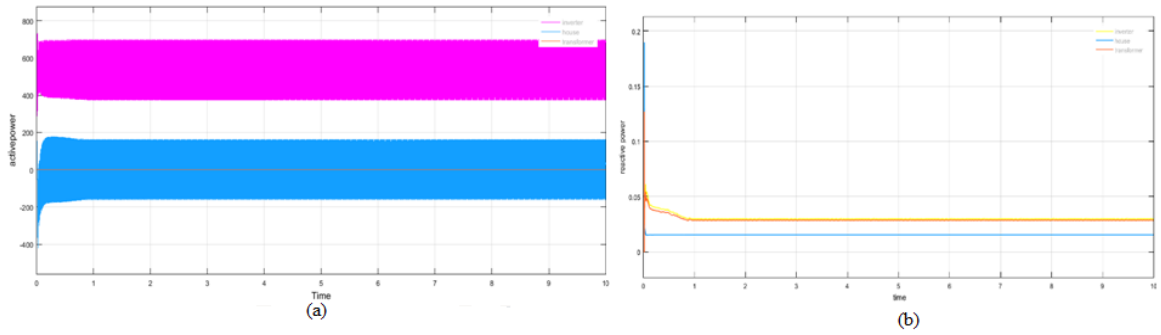


Fig. 5 Power curtailment of proposed SG System over time (a) APC and (b) Reactive Power Control.

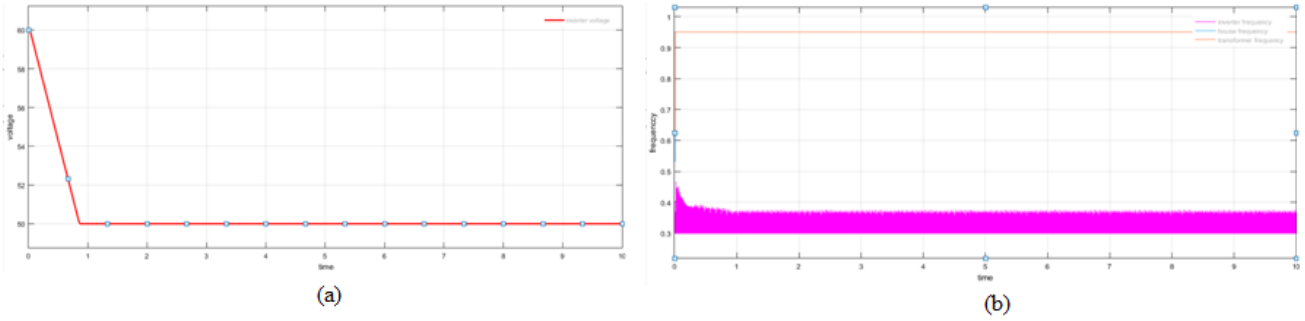


Fig. 6 Power Curtailment with respect to Voltage and frequency over time (a) Voltage Control and (b) Frequency Control.

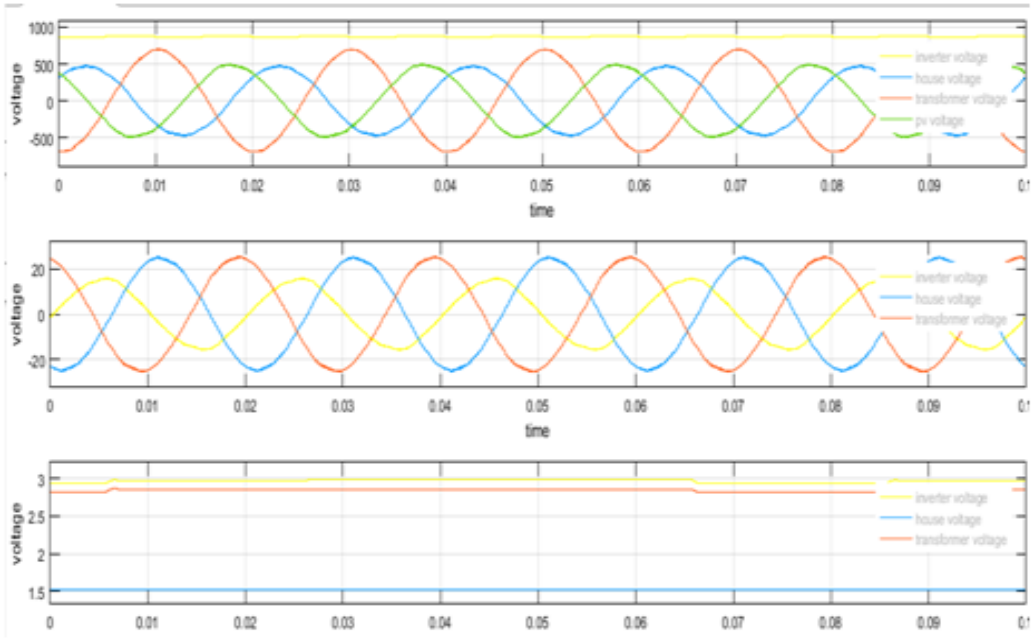


Fig. 7 Power curtailment performance of the proposed model with respect to grid voltage over time.

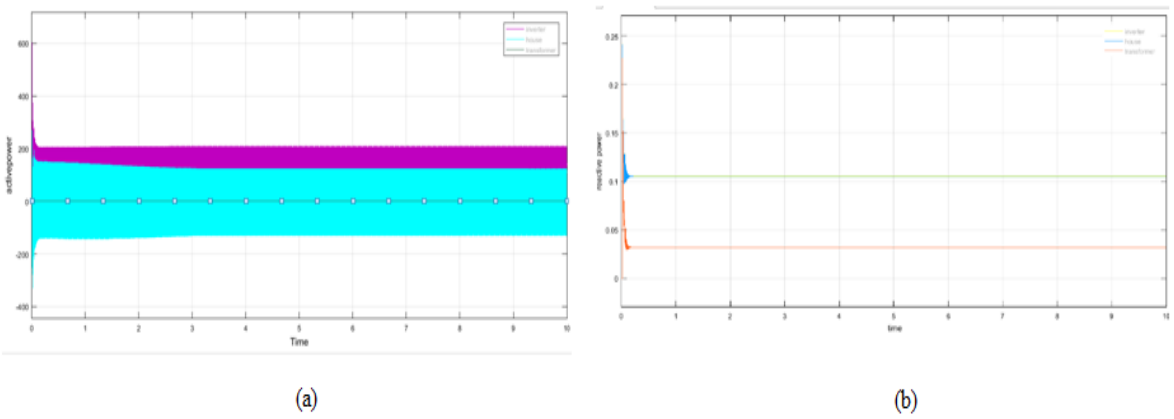


Fig. 8 Power de-curtailment of proposed SG system over time (a) APC and (b) reactive power control.

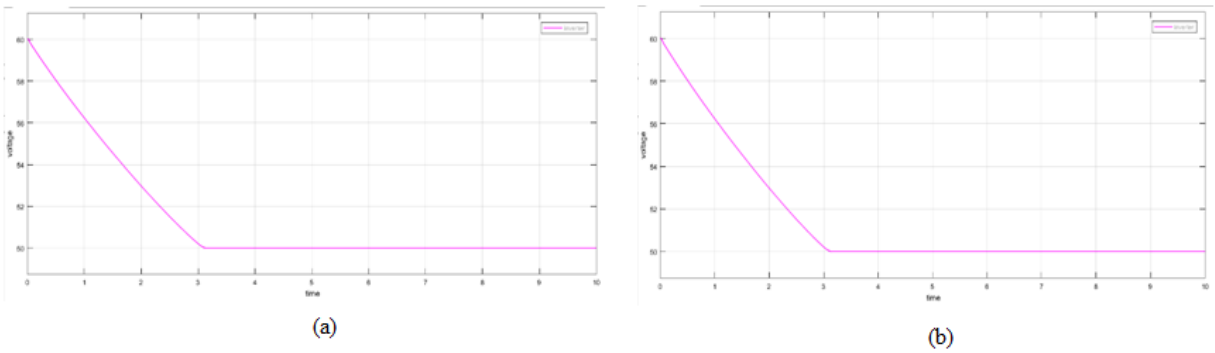


Fig. 9 Power de-curtailment with respect to voltage and frequency over time (a) Voltage Control and (b) Frequency Control.

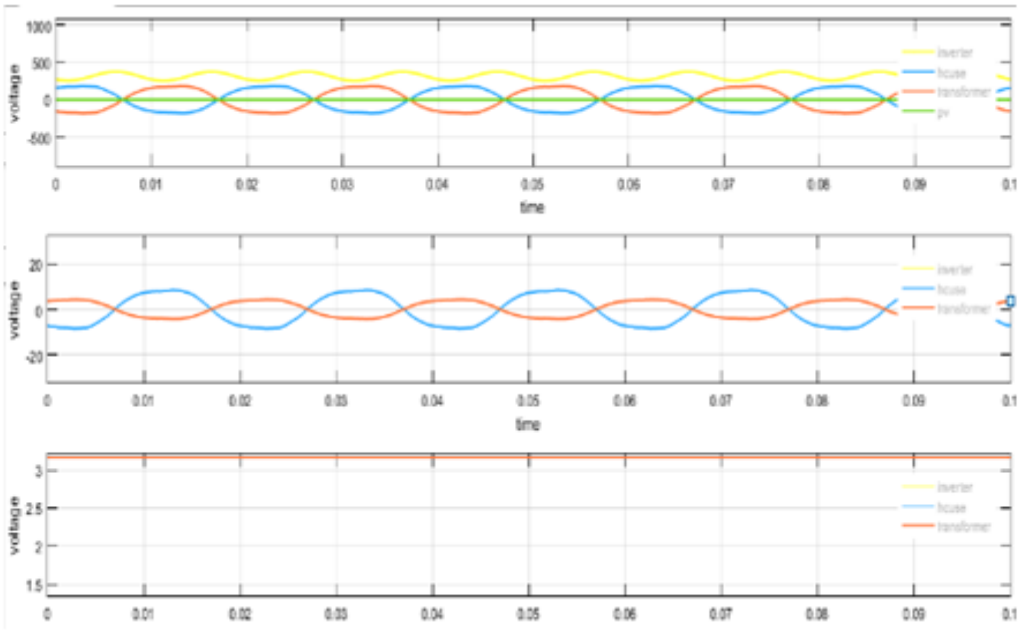


Fig. 10 Overall power de-curtailment performance of the proposed model with respect to grid voltage over time.

Conclusion

In this paper DG voltage control as well as frequency control through smart SPV inverter towards SG systems by means of proposed customized APC model have been performed successfully. Here, the active power curtailment and volt-watt controller was employed to curtail the voltage fluctuations and thus achieved the enhanced voltage profiles. Generally, production of over power results in over frequency problems and thus causes frequency deviations. The stability of the electricity grid was minimized by the uncontrolled frequency deviations. Therefore, through smart SPV inverter and the f-w controller, over-frequency issue was minimized and thus achieved regulated frequency over the smart grid system. In general, APC was implemented to balance the voltage fluctuations and frequency deviations. However, for large electricity grid systems, imbalance between voltage and frequency still exists. For regulating the issues in voltage & frequency maintenance, flexibility among high and low power generation was required. Thus, the proposed Customized APC model

overcomes the over-frequency and voltage issues using smart PV inverters. Outcomes of the experimental work verified effectiveness of the suggested model.

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