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# Distributed Incremental Adaptive Filter Controlled Grid Interactive Residential Photovoltaic-Battery Based Microgrid for Rural Electrification

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**ABSTRACT-** In this paper, a distributed incremental adaptive filter (DIAF) controlled utility interfaced photovoltaic (PV) battery microgrid system is presented with power quality features. From protection aspects, grid tied solar inverters are required to shut down at loss of the utility. However, the multi-purpose PV-battery system is developed to provide energy to the critical loads, even at loss of distribution network. The bidirectional controlled converter with a battery also mitigates the intermittency of a PV array under rapid variations in the weather. The extracted maximum power is supplied to the voltage source converter (VSC), which is transferred to the nonlinear loads and the utility. The distributed incremental adaptive filter is used to control the VSC with contribution of PV power and the battery. In addition, the DIAF control provides harmonics mitigation, load balancing and power factor improvement functionalities in order to deal with system connected with nonlinear loads. A PV power feed-forward (PVFF) term is incorporated in the current control for injection of active power to the utility as well as to improve the dynamic operation of residential PV-battery microgrid. The battery energy storage (BES) reduces the fuel bills and it is also utilized to provide smoothing attributes to the microgrid. The effectiveness of PV-battery microgrid is validated experimentally developed in the laboratory.

**KEYWORDS:** PV-battery microgrid, power quality and distributed incremental adaptive filter.

## I. INTRODUCTION

The use of renewable energy resources (RES) for generation of electricity, is the global sustainable and user friendly [1]. Various renewable energy sources (PV, wind and biomass etc.) are readily available in the nature and contribute to sustainable development. In addition, the cost of generated electricity through photovoltaic (PV) array is reducing rapidly. Therefore, there is large demand of the grid tied PV systems [2]-[4]. However, the variability of climate, leads the PV array power intermittence, which reduces the power output and serious problems in utility integration. Therefore, the PV industry has proved that the battery storage is the powerful solution in the coming years [5]. The batteries are deployed in a various kinds of PV applications, and soon it is likely that small residential PV systems furnish bulk demand of the battery energy storage [6]. There are various PV/battery residential systems that are commercially available, and they target at improving self-consumption of energy from the PV-battery systems. The microgrids operate in utility connected mode where they are tied with the main distribution grid and islanded modes depending upon the availability of the utility grid. Beside the mitigation of intermittency, the battery, is an important part to make the microgrid reliable, means under outage of PV array and utility, the battery is used to feed the power to the loads. In utility tied PV/battery system, the RES and battery are integrated close to the consumers

load rather than using long transmission lines for providing the power to the consumers. The most prominent benefit to include a battery energy storage (utility integrated with battery storage or off-grid) is the guarantee of energy during a utility failure [7]. The islanding occurs for very limited time span, although it provides reliability by regulating voltage and frequency and uninterrupted energy to local loads. However, in utility tied mode, an effective synchronizing technique is required for several power and industrial facilities. Generally, the power electronic converter is used to harvest the peak power from PV panel by tracking the optimum array voltage corresponding to the irradiance. However, here, VSC performs both the functions, extraction of maximum power from the PV array and feeds surplus power to the utility.

The outcome and benefits of proposed microgrid, are enlighten as follows.

- This microgrid provides continuous supply to the emergency loads in utility connected and standalone modes. The system operates even at outage of the distribution network and the control is switched from current control to voltage control. Therefore, it improves the operation adaptability of grid interactive PV-battery microgrid.
- Here, a simple seamless transfer passive detection technique is used, which requires only information of grid voltage, angle and frequency and does not require any additional telecommunication device for detection of islanding. Therefore, the operational cost is low and smooth transfer also protects loads from severe faults at transitions.
- Since the variation of phase and frequency, is natural phenomenon under outage and appearance of distribution network. Therefore, here a pseudo-linear-enhanced phase locked loop (PL-EPLL) based control is utilized to avoid such large transient as simple phase locked loop (PLL) experiences significant change in frequency and phase at recovery of the utility and may take large time to settle its normal value. The major problem in PLL, is that the extracted signals are processed within a single loop [22].

The utility-interactive PV-battery system assists in minimizing distribution losses as it feeds active power closeto load ends. Moreover, the RMS current in the distribution line is further minimized due to the functionalities of harmonics suppression, utility currents balancing, and compensation of reactive power locally. The harmonics suppression and load balancing functionalities also help in enhancing the current and voltage quality at PCC.

## II. TOPOLOGY OF PV-BATTERY MICROGRID

The topology of PV/battery system is explained in Fig. 1. Here, a PV array and bidirectional controlled battery bank are connected at DC link capacitor of VSC. A three-phase VSC is tied in parallel to the nonlinear load. Here, a lead-acid battery is selected due to its high current density, robustness and ability to deliver very high current. For conversion of DC power to AC, the distributed adaptive filter controlled VSC with interfacing inductor, is chosen. The insulated gate bipolar transistors (IGBTs) are selected for power converters. The R-C filter and interfacing inductors are selected for mitigation of switching voltages and currents ripples. The unpredictibility of weather condition, is addressed by utilizing the BES by providing the smoothing facilities. For mitigation of converter switching ripples from the utility voltage, a Rf-Cf filter is connected at the PCC. The performance of this microgrid is validated at various operating scenarios.

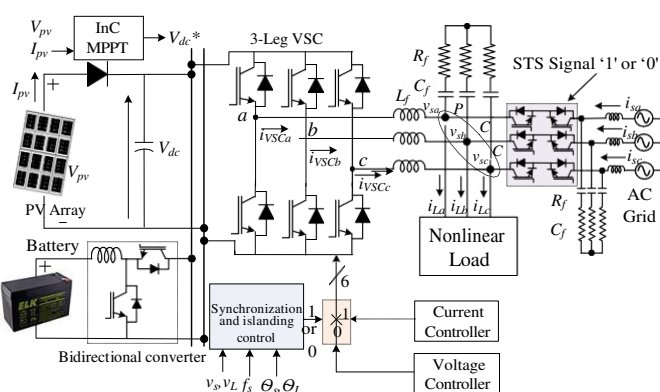


Fig. 1 Three phase utility interfaced PV-battery system

### III.CONTROL TECHNIQUE

This section discusses the distributed incremental adaptive filter (DIAF) based current control and dq based voltage control technique for VSC and cascaded proportional-integral (PI) control of a bidirectional converter of the battery. The utility reference currents are estimated by using contribution of the battery energy, PV array and energy required by the loads. The DC link voltage is regulated by the control of a bidirectional converter. The DIAF control regulates the utility currents such that VSC injects harmonics currents in anti-phase with the harmonics currents drawn by the loads. The estimation of synchronizing signals (in phase and quadrature) is necessary for the synchronization of VSC output to the utility and generation of switching logic.

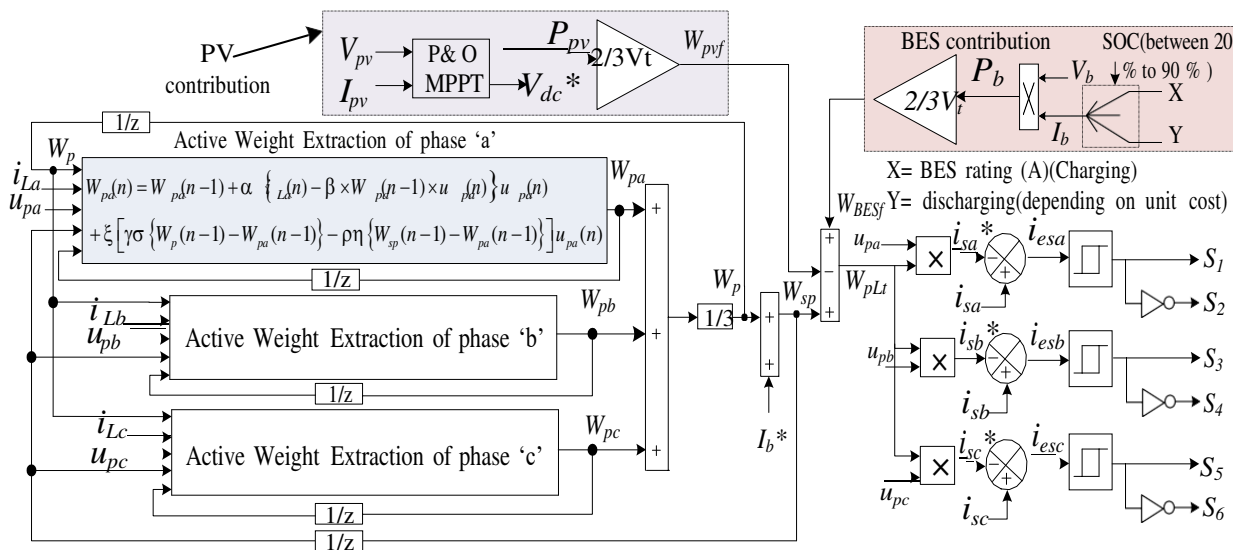


Fig. 2 Distributed incremental adaptive filter-based control

#### A. Distributed Incremental Adaptive Filter (DIAF) Based Current Control Algorithm

The distributed incremental adaptive filter (DIAF) based control technique ensures that the extracted PV power is fed to the utility grid. Moreover, this control is also responsible for reduction of harmonics in the utility. The principle of extraction of active weight component ( $W_{sp}$ ) of load currents, is based on a distributed incremental learning and feed-forward concept as shown in Fig. 2. An incremental adaptive learning based feedback error control with distributed properties for tracking error dynamics, is presented. In case of input disturbances, the adaptive incremental control furnishes a systematic concept for automatic adaptation of controllers in real time. The used algorithm compensates these disturbances and recovers the loop by feedback of extracted component. The variable adaptive filter is used within the context of incremental learning for the processing of load current. The algorithm for processing of load current must have low computational burden and need minimal communication between the system and controller. The coefficients of DIAF control are adapted in such a way so that the length of the filter is not increased and gives good convergence property of the algorithm. These coefficients play the crucial role in the design of adaptive algorithm. The computational burden and mean square are high if the value of coefficients, is too large. For synchronization to the utility, it is mandatory to acquire in-phase and quadrature synchronizing signals of the utility voltages. The amplitude of PCC voltage is derived as [8],

$$V_t = \{2(V_{sa}^2 + V_{sb}^2 + V_{sc}^2)/3\}^{1/2}$$

**B. Isolated Control of VSC**

The disappearance of the distribution grid is quite common in rural areas. Therefore, at outage of grid, the microgrid should have the capabilities to switched and operate in standalone mode without any disturbance. Therefore, after switching, the microgrid is controlled in islated mode to provide the continuous power to the local residential loads. The dq based islated control algorithm is shown in Fig. 3. Here, the PI controller is used to regulate the estimated  $v_d$  and  $v_q$  components of load voltages. The output of PI controller is considered as the  $i_d$  and  $i_q$  components of VSC, which are converted in VSC currents using the inverse Parks transformation.

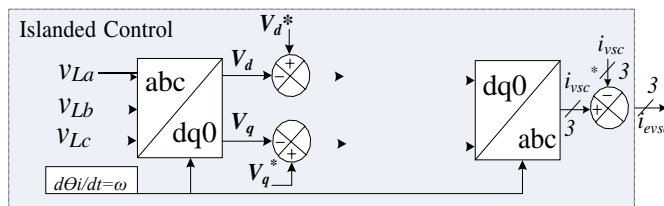


Fig.3 Isolated control

**C. Battery Control**

The primary function of control technique, is to manage the energy of the battery. However, the nominal voltage of the battery, is maintained in charging operation. The input to the voltage controller, is the comparison between sensed DC link voltage and reference voltage. The output of PI regulator, is reference battery current, out of which sensed battery current is subtracted and passes through current controller to get the duty cycle of a bidirectional converter.

**IV. RESULTS AND DISCUSSION**

A prototype of microgrid is developed in the laboratory in order to validate the usefulness of the, PV/ battery microgrid system with DIAF based control. A PV simulator (AMETEK) is used in the prototype with DSP (dSPACE-1103) controller for implementation of control algorithm. A lead-acid battery bank is tied at DC link capacitor via a DC-DC bidirectional converter. Moreover, a digital oscilloscope (DSO-DSO6010A) and a three- phase power quality analyser, are used to record the experimental results.

The prototype developed in the laboratory along with VSC, bidirectional converter, STS and PV array (AMETEK based), is presented in Fig. 6 and parameters are shown in Table-I.

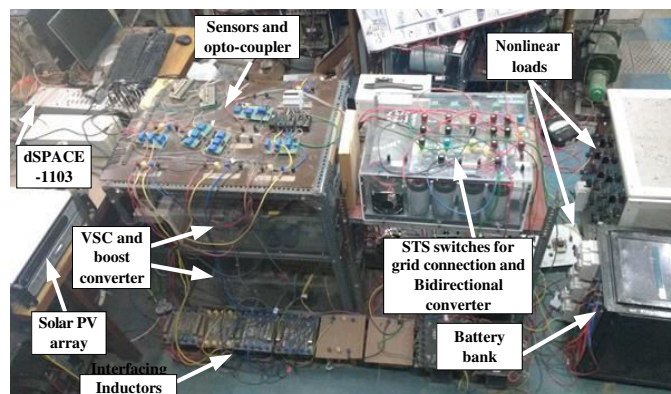


Fig.6 hardware photo of developed experimental rig

TABLE I  
PARAMETER OF PV-BES MICROGRID

PV voltage	400 V
PV current	10 A
PV power	4 kW
Battery parameters	240 V, 21 Ah
Bidirectional DC/DC inductor value	5 mH
DC link capacitor (C <sub>dc</sub> )	2250 $\mu$ F
DC link voltage	350 V
Utility voltage	230 V, 50 Hz,
R <sub>f</sub> & C <sub>f</sub> filter	4 $\Omega$ , 8 $\mu$ F,
Interfacing inductors	3.5 mH
Switching frequency	10 kHz
DIAF controller parameters	$\alpha=0.008$ , $\beta=0.9$ , $\gamma=$ $\rho=0.5$ , $\sigma=\eta=0.001$ , $\xi=0.2$ ,
Parameter of phase matching PI controller	$k_{pf}=0.5$ , $k_{if}=0.05$ ,
Parameter of standalone control	$k_{ps}=0.04$ , $k_{is}=0.02$ ,
Parameters of PL-EPLL controller	G1=100, G2=10, G3=0.5

### Comparative Assessment of PL-EPLL Controller and Conventional PLL Structure

Fig.8 illustrates the effectiveness of structure of PL-EPLL based control strategy as compared to conventional PLL at appearance of the grid. The estimation of frequency error ( $f_{err}$ ) and phase angle errors ( $\theta_{err}$ ) through the PL-EPLL controller and conventional PLL, are summarized. It is noticed that the phase angle and frequency errors estimated through PLL scheme, have large frequency transient and phase error as compared to structure of PL-EPLL during the transient. In this work, PL-EPLL control is also utilized as a filter, hence, the steady state accuracy is good in frequency and phase angle, which are extracted using PL-EPLL technique

### Experimental Performance under Sudden Recovery of Grid

Figs. 10 (a)-(d) present transitions of VSC from standalone to grid connected mode at sudden recovery of distribution network. The phase angle of load voltage, is regulated according to the angle of utility voltage as per the standard. Fig. 10 (b) presents the state in which the grid voltages ( $v_{sa}$ ,  $v_{sb}$ ,  $v_{sc}$ ) are appeared and STS is switched from '0' to '1' as amplitude, voltage angle and frequency of grid voltage, are in the specified values. The battery and PV parameters are maintained under outage, which are shown in Fig. 10 (c). The grid current ( $i_{sa}$ ), VSC current ( $i_{VSCa}$ ) PV current ( $i_{pv}$ ) and BES current ( $i_b$ ) are presented in Fig. 10 (d). The structure of  $i_{VSCa}$  becomes different as it injects harmonics power required by nonlinear loads as the fault from the distribution network is cleared. The battery is shifted from charging to the non-operating zone. The load power is uninterrupted throughout the process, islanding to utility tied mode and vice-versa.

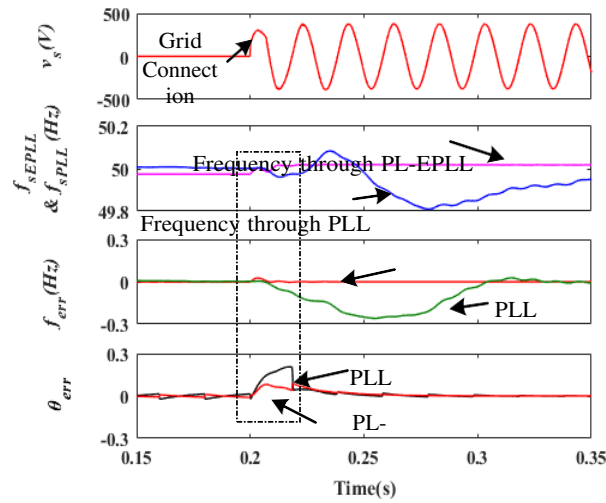
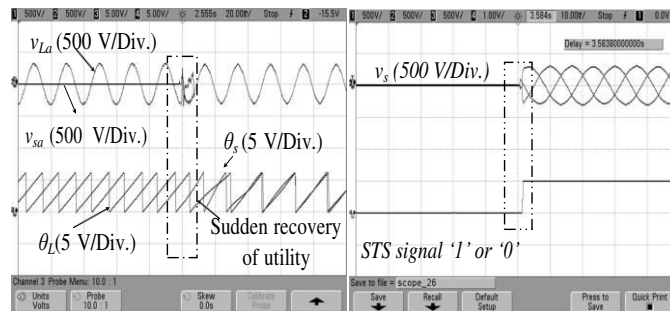
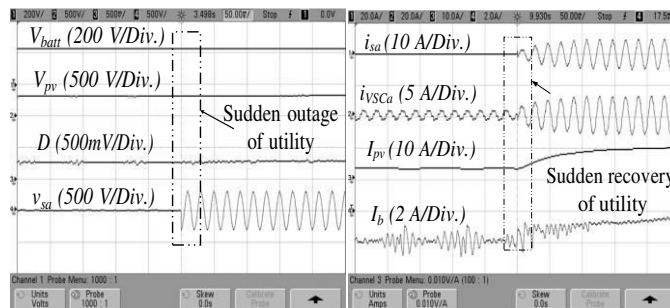


Fig.8 Assessment of proposed controller and conventional PLL structure at sudden connection of utility grid.



(a)

(b)



(c)

(d)

Fig.10 (a)-(d) Test results at transition from Islanded to utility interactive mode

## V.CONCLUSION

The distributed incremental adaptive filter (DIAF) based control of residential PV/battery microgrid system for rural electrification, has been demonstrated for its satisfactory operation. The focus of this topology has proved continuous supply by integrating the battery back-up with a PV array even under the outage of PV array and utility grid. The charging and discharging of the battery depending upon the state of charge (SOC) level, have been decided by the cascaded PI control. Test results of extracted PV energy and dynamic load and insolation change are studied for validation of control technique. Moreover, the power quality indices are provided, which are within limit of the IEEE-519 standard.

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