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Distributed Storage System with Solar Photovoltaic Energy Source

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***Abstract*—The management of Renewable Energy Sources (RES) and storage systems in order to connect to an LV distribution network imposes several challenges for the end-user. In addition, the nonlinear nature of the power electronic interfaces and the end-user loads create Power Quality issues in LV distribution network. In this paper, a power electronic device is proposed as a solution to the end-user for the management of RES, storage and for the mitigation of the Power Quality. The device, named Distributed Storage system, is connected in parallel to the end-user and the network. It facilitates online and island mode of operations. The device can manage injection of power into the network, of a RES, such as a PV, charging and discharging of a storage system and mitigate the Power Quality issues of the end-user by acting as a shunt active filter. The system structure, design, and control strategies are dealt with in this paper along with the description of hardware prototype realized.**

Keywords—Distributed Storage System, Power Quality, Shunt Active Filter, Solar Photovoltaic RES, Storage System

I. Introduction

With the advancements in smart grid technologies, the end-user in a power system is becoming a more active entity called prosumer [1]. According to the European Union (EU) renewable energy directive, the countries of EU agreed on a new renewable energy target of at least 27% of EU's final energy consumption by 2030 [2]. Through this initiative, the EU countries are providing initiatives for the end-user to install renewable energy sources. Typically, in Low Voltage (LV) distribution network, the end-user can generate the electrical energy from renewable sources, which is mostly dominated by the Photovoltaic (PV) energy generation. The end-user can operate completely in island mode with PV and a storage system, hence there is a need for managing both the energy storage and solar energy produced. However, in grid-connected mode, the end-user can inject the PV power produced into the grid or store it into the storage system for later use. In addition, the end-user needs to facilitate a smooth connection to the network by providing an ideal Load.

In reality, the power from PV generation is injected into the grid using power electronic converters and these cause power quality issues in the network at Point of Common Coupling (PCC) [3]. Moreover, the end-user loads are mostly power electronic which has high efficiency but draws nonlinear currents [4]. Inherently, these nonlinear currents cause disturbances in the distribution network leading to system instability. Hence, there is a necessity for the end-user to maintain power quality levels of the Load. [5]. In addition, the end-user in a smart grid needs to participate in providing ancillary services to the grid and also curtail part of his load when required by providing demand response.

With these challenges posed, there is a need for a device, which can manage all these requirements at the end-user level. Several system topologies are proposed in literature, to handle power quality issues, shunt active filters along with series unit is proposed in [6], grid-tied PV converters with active filtering is proposed in [7], new power quality device which can act in LV distribution system and also at end-user is proposed in [8], while the analysis of a shunt storage system is given in [9]. Other proposals for distribution system are given in [10-14], however, they can manage one or two requirements, but not all the Power Quality issues. Moreover, a majority of these systems in literature are targeted to three phase systems.

In this paper, a new device, called Distributed Storage (DS) System integrated with Photovoltaic (PV), is introduced. This device is installed in parallel to the end-user and the LV distribution network and it has the capability to manage the solar energy produced and the storage system. Depending on the network conditions, the device can go to island mode to supply the entire load and reconnect back to the network (online mode) when the Power Quality of the network is enough good. It has also the functionality to inject the PV power into the network and it can also work as shunt active filter to compensate load harmonic currents or works as STATCOM by supplying entire reactive power to the load. With these functional capabilities packed in a single device, DS with PV can be proposed as a unique solution to address the requirements of an end-user. In particular, this paper deals with the preliminary hardware design and control system realized for the system.

This Paper is organized into the following sections. Section II describes the structure of DS system. Section III describes the component level system design. Section IV describes the hardware prototype realized, in Section V the control strategies proposed for the system are given. Section VI closes the paper with a conclusion.

II. Distributed Storage (DS) System

The block diagram of the Distributed Storage (DS) System is shown in Fig. 1. The system consists of Static Switch (SS) which can be used to connect or disconnect the end-user from the network. A Front-End Converter (FEC) serves as an interface between the device and the network. The DC bus acts as a common point for energy exchange between energy sources and the FEC. The energy sources: Photovoltaic Panels (PV) and Battery Energy Storage System (BESS) are connected to the DC bus through PV converter and BESS converter.

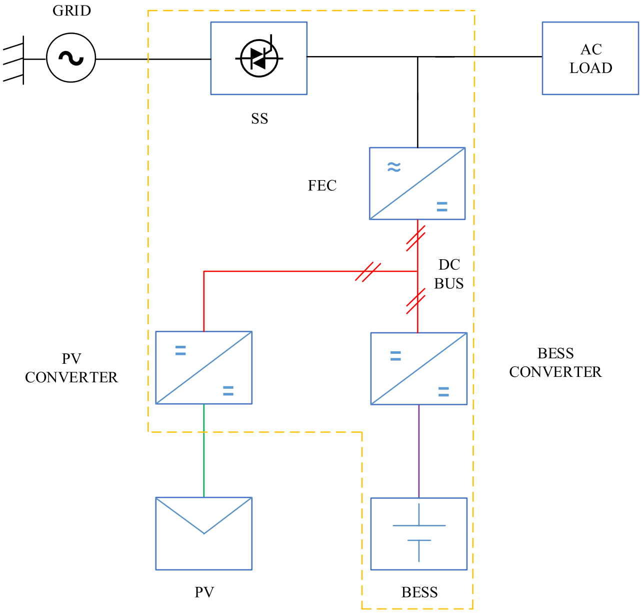

Fig. 1 Distributed Storage System: Block diagram

A. Detailed System Topology

The detailed system topology is given in Fig. 2. As can be seen, the static switch is realized using a back to back connected thyristor (SS) [15].

The FEC is realized by H-bridge with IGBT legs (T1 and T2) for bidirectional control, this is connected to the network using a switching inductance and a filter capacitor. The DC bus is made up of three capacitors (C1, C2, C3).

The BESS converter consists of a single IGBT leg module (T3), depending on the use of top or bottom switch, the converter can be used in boost or buck mode for discharging and charging the batteries respectively. The capacitor (C4) and inductor (L2) are connected between the converter leg and Batteries, which acts as filters for controlling the converter.

The PV converter consists of a single IGBT leg module (T4). It is used in boost mode and hence, only bottom switch is used, the top switch acts as a diode. The capacitor (C5) and inductor (L3) are connected between the converter leg and PV panels, which acts as filters for controlling the converter.

III. System Design

In Italy, even if a single-phase end-user connected to a LV distribution network has in general a maximum contractual power of 6kVA, the most common contractual power adopted by the end-user is 3kVA. Hence, 3kVA is taken as the reference power to design the system. The rest of the components are design as follows.

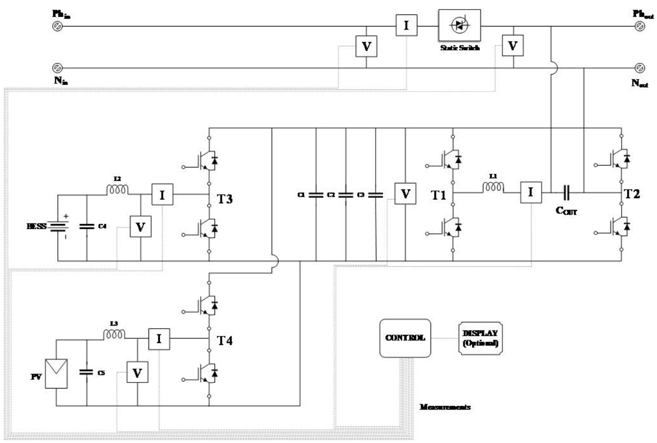

Fig. 2 Distributed Storage System: System topology

A. DC Bus Capacitor

The main aspect in designing the DC bus capacitor is the DC bus voltage. In a LV distribution system, the line voltage value is 230V rms, and the peak value is 325V.

The DC bus voltage should be higher than this value for the FEC not to go into saturation mode. Usually, the line voltage can vary up to ±10% and the peak value can reach up to 357V. Considering a safety factor of 1.25, DC bus voltage can be computed to be 357x1.25 = 446.25V.

Considering practical aspects, this value is rounded off to 450V and used as DC bus voltage. In order to compute the DC bus capacitance, the energy δE that must be supported by the DC bus is essential. The device nominal active power is 3kW and estimating support of up to five fundamental periods (100ms), δE is computed using the energy balance equation of the capacitor (1).

$$C_{dc} = \frac{2\times\delta E}{V_{max}^2 - V_{min}^2} = \frac{2\times 3kW\times 100ms}{470^2 - 430^2} = 16.6mF \tag{1}$$

where C_{dc} is the calculated DC bus capacitance, δE is the energy that needs to be extracted from the DC bus. V_{max} is the maximum DC bus voltage and V_{min} is the minimum DC bus voltage. The PV power injection is designed to be injected till 470V, hence, V_{max} is taken to be 470V (the reason for this is explained in Section V). For V_{min}, a variation of 5% from the set-point value of DC bus is taken as design value and is calculated to be 430V. From this, the value of DC bus capacitance is computed to be 16.6mF.

In the market, the standard electrolytic capacitors available are of 6800uF. In order to realize the DC bus, three of these capacitors are connected in parallel, leading to a total capacitance of 20.4mF.

B. AC Line Switching Inductance

The AC line switching inductance is used to interface the device to the network and its value is calculated using (2).

$$L_{ac} = \frac{V_{dc}}{4\times f_{sw\_i}\times I_{rpp\_ac}} = \frac{450}{4\times 20k\times 5.625} = 1mH \quad (2)$$

where L_{ac} is the switching inductance, V_{dc} is the DC bus voltage, f_{sw_i} is the FEC switching frequency and I_{rpp_ac} is the maximum peak to peak ac ripple current.

Considering V_{dc} = 450V, f_{sw_i} = 20kHz, I_{rpp_ac} = 5.625A (which is about 25% of device nominal current), the value of the inductance is calculated to be 1mH.

C. PhotoVoltaic Sizing

Considering the DS system sizing, the size of PV array is considered to be 1.5kW. This sizing can be relaxed, respecting the device power limits. However, the sizing of the PV plant depends on several factors. The major concern can be from the network operator because of the loading capacity of the transmission lines. Also, in Italy, a residential end-user in LV network can install a PV plant up to his maximum contract power. An interesting study for sizing the PV plant and the converter is given in [18-19]. The PV plant can be realized using standard available solar panel. Current PV panel technology can have approximately 300W max power with open circuit voltage V_{oc} around 50V. For practical realization, 5 to 6 solar panels can be used in serial-parallel combination to obtain a PV panel output voltage of 100V.

D. PV Switching Inductance

The PV converter works in boost mode. Hence, the inductance value can be determined using equation (3).

$$L_{pv} = \frac{V_{pv\_in}\times(V_{pv\_out}-V_{pv\_in})}{V_{pv\_out}\times f_{sw\_pv}\times I_{rpp\_pv}} = \frac{100\times(470-100)}{470\times 20k\times 1} = 3.94mH \quad (3)$$

where L_{pv} is the PV switching inductance, V_{pv_in} is the voltage across PV array, V_{pv_out} is the DC bus voltage at which the PV power is injected, f_{sw_pv} is the switching frequency of the PV converter and I_{rpp_pv} is the maximum peak to peak ripple current.

Considering V_{pv_in} = 100V, V_{pv_out} = 470V, f_{sw_pv} = 20kHz and I_{rpp_pv} = 1A, the L_{pv} is computed to be 3.94mH. Therefore, it can be rounded to 4mH.

In the hardware prototype, the inductance is realized with a value of 1.5mH, this is due to the commercial availability and cost. Hence this comes at a price of increasing the ripple current Irpp_pv to 2.62A.

E. Battery Storage

Battery storage is designed based on the commercially available lead-acid batteries. Six batteries of 12V, 12Ah are chosen for the storage. In total the Battery Storage can provide a total of 864Wh capacity which is enough for a 3kW application to provide power for up to 17 minutes under full load condition.

F. Battery Storage Switching Inductance

To use the same inductance for the boost and buck operation of the converter the inductor design is done using the buck operation with a fixed switching frequency and later this inductance value is used to calculate the switching frequency for boost mode.

Considering the buck mode operation for charging, the inductance value required is given as equation (4).

$$L_{bat} = \frac{V_{bat\_out}\times(V_{bat\_in}-V_{bat\_out})}{V_{bat\_in}\times f_{sw\_bat\_buck}\times I_{rpp\_bat}} = \frac{80\times(450-80)}{450\times 20k\times 1} = 3.28mH \quad (4)$$

where L_{bat} is the battery switching inductance, V_{bat_out} is buck converter output voltage and V_{bat_in} is input voltage to the buck converter which is the DC bus voltage, $f_{sw\_bat\_buck}$ is the switching frequency in buck mode and I_{rpp_bat} is the peak to peak ripple current.

Considering V_{bat_out} = 80V, V_{bat_in} = 450V, $f_{sw\_bat\_buck}$ = 20kHz, I_{rpp_bat} =1A, L_{bat} is computed to be 3.28mH. In the hardware prototype the inductance is realized with a value of 1.5mH, this is due to the commercial availability and low cost. Hence this comes at a price of increasing the ripple current I_{rpp_bat} to 2.19A.

The second part involves calculating the switching frequency for boost operation using this inductance value obtained. From the boost mode operation, this can be derived using equation (5).

$$f_{sw\_bat\_boost} = \frac{V_{bat\_in}\times(V_{bat\_out}-V_{bat\_in})}{V_{bat\_out}\times L_{bat}\times I_{rpp\_bat}} = \frac{80\times(450-80)}{450\times 3mH\times 5} = 4.38kHz \quad (5)$$

where L_{bat} is the battery switching inductance, V_{bat_out} is boost converter output voltage and V_{bat_in} is input voltage to the boost converter which is the battery voltage, $f_{sw\_bat\_boost}$ is the switching frequency in buck mode and I_{rpp_bat} is the peak to peak ripple current.

Considering V_{bat_out} = 450V, V_{bat_in}= 80V, L_{bat} = 3mH, I_{rpp_bat}=5A, $f_{sw\_bat\_buck}$ is computed to be 4.38kHz. This frequency is adjusted to 4.5kHz for practical implementation in a digital controller.

IV. HARDWARE IMPLEMENTATION

Fig. 3 shows the experimental prototype of the Distributed Storage System realized. The prototype is built inside a standard electrical metal cabinet installation.

The cabinet is split into two sections, right and left. The right consists of power converters mounted and left part consists of control boards and contactors for the device startup. In detail, on the right part of the cabinet, Power Electronic IGBT switches for FEC, BESS converter and PV converter are mounted on a heatsink casing and connected to the DC bus capacitors through a thick flat metal bus bar.

The DC bus capacitors are mounted behind this bus bar. Towards the middle right of the cabinet, the prototype consists of a thyristor-based static switch, mounted externally on a heat sink. On the metal heat sink casing, the drivers for the power electronic switches are mounted. The voltage sensors are mounted above the drivers. The currents sensors are attached to the metal plate connectors of the switches at their entry point. Three inductors for AC switching inductor, Battery switching inductor and PV switching inductor are mounted below the heat sink casing.

The battery storage is placed on the bottom of the cabinet on a metal bed, they are attached to the base using a Velcro strap. Coming to the left side, on the top we have DSP board can be seen which is designed for control, driving power switches and for measurements. Below this board, a metal railing is connected on which a DC power supply is mounted which supplies power to the control board and the contactors. On the same railing contactors and connectors are fixed. Close to the railing DC bus pre-charge resistor can be seen. External to the cabinet a double pole single throw switch and an electrolytic capacitor can be seen. These two devices are used to interface the device with the cables from the PV panels.

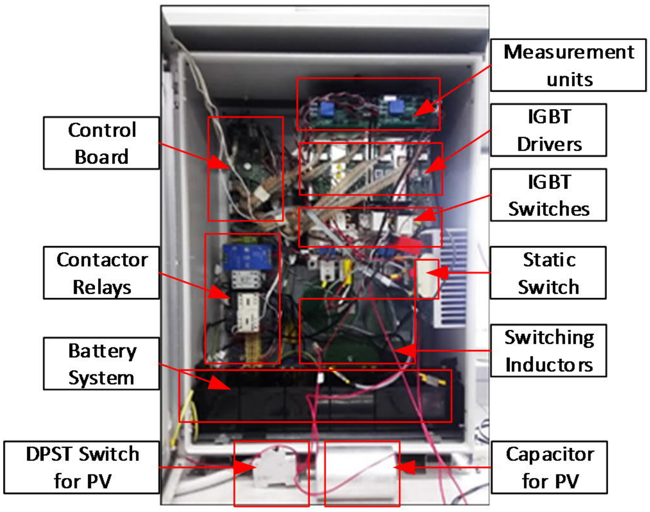

Fig. 3 Distributed Storage System Hardware Prototype

V. Control Design

The control of the DS system with PV can be considered as controlling three independent converters. This can be possible by using different setpoints of DC bus for the converters. The PV converter control must extract maximum power from PV and inject it to the DC bus. The BESS Converter, depending on the mode of operation must control charging and discharging of the batteries. The FEC plays crucial role and the control must perform several functionalities. The control design adopted for these converters are as follows.

A. Management of Energy resources

In order to manage effectively the FEC, storage and the PV power, DC bus voltage value can be taken as reference for the control design. This enables to derive independent control algorithms for the FEC, PV and BESS converters respectively. For the BESS converter and FEC, V_{dc} reference is set to 450V and for the PV converter, it is set to 470V. This enables to independently control the converters and can be demonstrated using the following example. Consider the PV power is injected into the DC bus, the voltage of DC bus raises to 470V, the BESS controller and FEC controllers see the rise in DC bus. The independent controllers respond to this event by regulating the DC bus voltage to 450V, this regulation is done by charging batteries depending on their state of charge and the FEC injecting this power to the network. In the event, the PV power is not available, and the FEC needs to extract power from DC bus to provide functionalities, in this case, the DC bus value goes below 450V and depending on the state of charge, the batteries starts discharging to regulate the DC bus at 450V.

B. PV Converter Control

The designed control algorithm includes three stages. The first stage consists of a Maximum Power Point Tracking Algorithm. Over a wide variety of algorithms available, Perturb and Observe method is considered for its simplicity in its implementation and sufficient accuracy [16]. This algorithm is used to obtain a voltage reference value. This voltage reference value is filtered and is fed through a PI controller (second stage) in order to convert it to a current reference. In the third stage, this current reference is fed through a model based controlled to obtain the duty for the PWM. The block diagram of the algorithm is shown in Fig. 4.

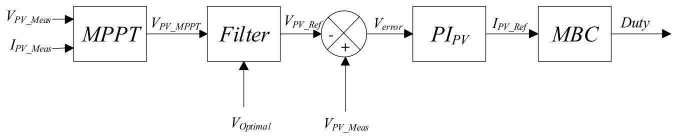

Fig. 4 Control Algorithm for PV block diagram.

Notice that the input voltage control loop works quite differently compared to conventional feedback used in output voltage control. Under this control scheme, when the PV panel voltage (V_{pv_Meas}) tends to go higher than the reference panel voltage (V_{pv_ref}) set by the MPPT algorithm, the control loop increases the panel current command (I_{pv_ref}) and, thereby, controls the panel voltage at its reference level (V_{pv_ref}). When the panel voltage tends to go lower than the reference, the control loop reduces the panel current command in order to reestablish the panel voltage to its reference level.

C. BESS Converter Control

As explained the Battery converter control needs to perform charging and discharging functions. The control algorithms designed are as follows.

1) Battery Charging: For charging, the BESS converter is operated in buck mode by controlling the high side switch. Standard charging methods are used which has two modes of charging, Constant-Current, Constant-Voltage (CC-CV) respectively. These modes are adopted to the control strategy depending on batteries state of charge [17]. In constant current charging mode, the batteries are charged with constant current, while the terminal voltage increases to the desired set point. The duty cycle for this operation mode is generated using equation (6).

$$D_{buck} = \frac{\frac{(i_{ref} - i_{Lbat}) \times L_{bat}}{T_s} + V_{bat}}{V_{dc}} \quad (6)$$

where D_{buck} is the duty cycle generated and is used to control the high side switch of the BESS converter for buck operation to charge the batteries, i_{ref} is the reference constant current (usually it is nominal charging current for the batteries coming from data sheet), i_{Lbat} is the measured current across the battery switching inductance, L_{bat} is the battery inductance, Vbat is the measured battery voltage and V_{dc} is the measured DC bus voltage.

During the constant voltage mode of charging, the charging of the batteries is controlled by a simple PI controller, as shown in Fig. 5, to provide the current reference to extract the power from the DC bus. This current reference is then used in (6) to generate the gate signals.

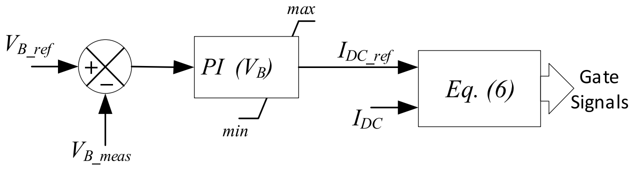

Fig. 5 Control block diagram: Battery CV charge operation.

2) Battery Discharging: The discharging of the batteries is controlled by cascaded PI controller, as shown in Fig. 6. The outer PI works on DC bus voltage to generate a reference current to be injected into the DC bus, this is fed to an inner PI which generates duty cycle for Low side switch of BESS converter for boost mode operation.

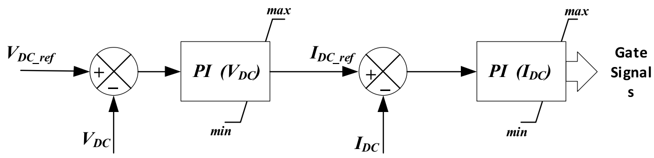

Fig. 6 Control Block diagram: Battery discharge operation.

D. FEC Control

The control for PV and batteries during online or island mode of operation is the same, however, FEC works as a current source during online mode while during island mode, it works as a voltage source. A model-based controller (MBC) is derived to generate duty cycle for FEC [17]. This is common for both online and island mode of operation. The equation of the MBC derived for the FEC is:

$$V_c = \frac{\frac{(i_{ref\_inv} - i_{meas\_inv}) \times L_{ac}}{Ts_{inv}} + V_{dc} + V_{ref}}{2 \times V_{dc}} \tag{7}$$

where V_c is the control voltage fed to the PWM, i_{ref_inv} is the reference current generated and i_{meas_inv} is the measured current across the device output terminals, V_{dc} is the DC bus voltage and V_{ref} is the Voltage reference, typically V_{ref} is the network voltage in online operation mode and a digitally synthesized sine wave in offline operation mode.

1) Online Mode of Operation: Under online mode, the static switch is closed and the DS system along with the Load is connected to the network. By modulating the reference current to the MBC, various functionalities can be obtained. Each functionality and the relevant control strategy applied is as follows. The block diagram for reference currents generated is presented in Fig. 7.

a) DC bus control/PV power injection: The DC bus control by FEC is important in order to inject the PV power into the network. Also, under no availability of PV power, the batteries can be charged through the network. The controller regulates the DC bus value to its setpoint if there is an increase/decrease in the DC bus voltage by injecting/extracting the power from the network. This controller is derived using a simple PI controller on the DC bus voltage to generate a reference current. In order to inject or extract this current synchronous to the active power, this value is multiplied with sine generated by a PLL and it forms a reference current for the FEC denoted as Iref_DC.

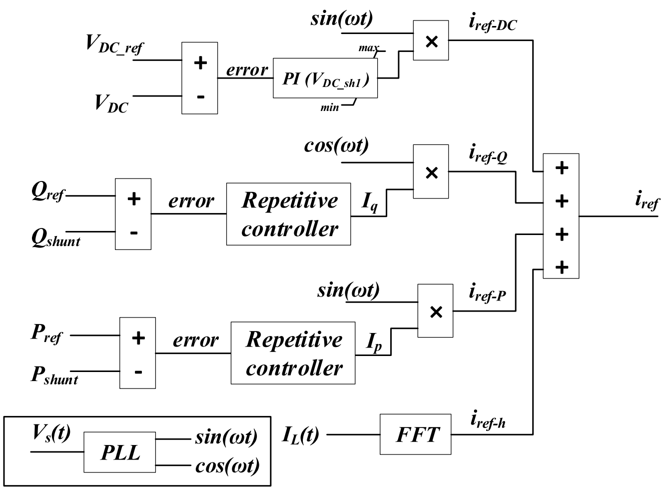

Fig. 7 Control block diagram: FEC reference current generation in online mode

b) Peak Shaving: Demand response is an important aspect in the smart girds, the end-user can curtail load on the request of the Distribution System Operator or in the case of absorbing more power than the contractual power. In order to achieve demand response, the peak shaving function can be performed by measuring the active power absorbed from the source and is compared to the set value. It is passed through a repetitive controller to provides a reference current which is multiplied by sine signal generated by PLL, the output of this controller gives active current reference I_{ref_P} to be injected into the load for curtailing the additional load power usage from the network.

c) Reactive Power Injection: The DS system can compensate entire reactive power absorbed by the load. In order to achieve this, reactive power component from the load power is extracted using the instantaneous power theory. This value compared to the measured one is passed through a repetitive controller to generate a reference current. Since this is reactive power component, the current needs to be injected in quadrature to the network voltage, hence, it is multiplied by a cosine signal generated from the PLL and reference current I_{ref_Q} is generated.

d) Harmonic Compensation: The DS system can compensate entire harmonics of the load. For this, the load current is passed through a simple FFT filter to extract harmonic currents. These components are passed as a reference current I_{ref_h} in order to be compensated.

All these current components are then added and fed to MBC as shown in equation (7) which provides a control voltage signal to drive the PWM of the FEC. In this way, the functionalities of the FEC in online operation mode are achieved.

2) Island Mode of Operation: During Island operation mode, the FEC terminal voltage, frequency and magnitude should be controlled. Therefore, the control method reported in Fig. 8, based on a cascaded controller with load current feedback, is implemented in order to avoid voltage drop under load variation for Island operation mode. The Vref in offline is generated from previously stored values of the network voltage and frequency.

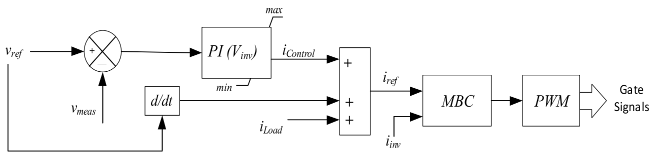

Fig. 8 Control block diagram: FEC reference current generation in island mode

VI. Conclusion

To meet the challenges of managing energy sources and mitigation of power quality issues, a new solution, Distribution Storage system with PV is proposed. Though this paper, the device structure, component design and control strategies are addressed. Also, an experimental prototype realized is described. Having the capability of managing PV power and storage system, the device can work in online and island mode of operation. In addition, the device can mitigate power quality issues by acting as a shunt active filter. With these functionalities, the device can surely be a unique solution for challenges posed on end-user in an LV distribution network.

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