Integration and Operation of a Three-Level NPC Inverter with Advanced Control Strategy for DC-AC Distribution Applications

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Abstract—This study is concentrated on integration and operation of a three-level neutral-point-clamped (NPC) inverter maximum power point trackers (MPPTs) for dc-ac distribution applications. In a dc-distribution system, a neutral-point-clamped inverter is required to control the power flow between dc bus and ac grid, and to regulate the dc bus to a certain range of voltages. A novel regulation mechanism according to the inverter inductor current levels to reduce capacitor size, balance power flow, and adjust load variation is proposed. A novel control algorithm for the proposed system is also implemented in order to control the power delivery between the solar PV, battery, and grid, which also provides maximum power point tracking (MPPT) operation for the solar PV.

Index Terms—Battery storage, solar photovoltaic (PV), space vector modulation (SVM), three-level inverter, dc-ac distribution applications.

I. INTRODUCTION

Several types of non conventional sources of energy, such as photovoltaic (PV), wind, tidal, and geothermal energy, have attracted a lot of observation over the past decade [1]–[3]. Among these natural resources, the PV energy is a main and appropriate non conventional sources of energy, for low-voltage dc-distribution systems, promising to the merits of clean, calm, pollution free, and generous. In the dc-distribution applications, a power system, including renewable distributed generators (DGs), dc loads (lighting, air conditioner, and electric vehicle), and a inverter, in which two PV arrays with maximum power point trackers (MPPTs) are implemented. However, the i–v characteristics of the PV arrays are nonlinear, and they require MPPTs to draw the maximum power from each PV array.

In three-phase practice, two types of power electronic arrangement are commonly used to transfer power from the non conventional sources of energy to the grid: single-stage and double-stage conversion. In the double-stage conversion for a PV system, the starting stage is usually a dc/dc converter and the second stage is a dc/ac inverter. The function of the dc/dc converter is to smoothen the maximum power point tracking (MPPT) of the PV array and to produce the appropriate dc voltage for the dc/ac inverter. The purpose of the inverter is to generate three-phase sinusoidal voltages or currents to transmit the power to the grid in a grid-connected solar PV system or to the load in a stand-alone system [3]–[5]. Scientific high tech progress and environmental concerns drive the power system to a paradigm shift with more renewable energy sources added to the network by means of distributed generation (DG). These DG units with coordinated control of domestic generation and storage space form a micro grid. In a micro grid, power from different renewable energy sources such as fuel cells, photovoltaic (PV) systems, and wind energy systems are interfaced to grid and loads using power electronic converters. A grid connected inverter plays an important role in exchanging power from the micro grid to the grid and the connected load. This micro grid inverter can either work in a grid sharing mode while supplying a part of local load or in grid injecting mode, by injecting power to the main grid.

Maintaining power quality is another important feature which has to be addressed while the micro grid system is connected to the main grid. The expansion of power electronics devices and electrical loads with unbalanced nonlinear currents has demean the power quality in the power distribution network. Moreover, if there is a considerable amount of feeder impedance in the distribution systems, the circulate of these harmonic currents distorts the voltage at the point of common coupling (PCC). At the same time, industry automation has reached to a very high level of sophistication, where plants like automobile fabricate units, chemical factories, and semiconductor industries require clean power. For these utilization, it is essential to compensate nonlinear and unbalanced load currents.

This paper is concerned with the design and study of a grid-connected three-phase solar PV system integrated with battery storage using only one three-level converter having the capability of MPPT and ac-side current control, and also the ability of
controlling the battery charging and discharging. This will result in lower cost, better efficiency and increased flexibility of power flow control.

II. ANALYSIS OF A THREE-LEVEL INVERTER

A. Three-Level Inverter

Since the establishment of three-level inverters in 1981 [6], [7], they have been widely used in several applications, such as: motor drives, Static compensator (STATCOM), HVDC, pulse width modulation (PWM) rectifiers, active power filters (APFs), and the non conventional sources of energy applications [7], [8]. Fig. 1(a) shows a model of three phase three-level neutral-point-clamped (NPC) inverter circuit topology. The converter has two capacitors in the dc side to produce the three-level ac-side phase voltages. Generally, the capacitor voltages are assumed to be balanced, since it has been reported that unbalance capacitor voltages can influence the ac-side voltages and can produce unexpected behavior on system parameters such as even-harmonic injection and power ripple [7], [9]. Many papers have discussed methods of balancing these capacitor voltages in various applications [6], [7], [9]–[16].

B. Voltage balance of Capacitors

Several methods have been proposed to balance the capacitor voltages using modulation algorithms such as sinusoidal carrier based PWM (SPWM) or space vector pulse width modulation (SVPWM) [17]. In sinusoidal carrier based PWM (SPWM) usance, most of the algorithms are based on injecting the appropriate zero-sequence signal into the accentuation signals to balance the dc-link capacitors [12], [13], [16], [18]. In SVPWM applications, a superior understanding of the results of the switching options on the capacitor voltages in the vector space has resulted in many algorithms proposed to balance capacitors voltages in the three-level NPC inverter. These include capacitor balancing using conventional SVPWM, virtual SVPWM (VSVPWM) and their composition [14], [15], [19]. In vector control theory, ideally, the inverter must be able to produce the voltage output contiguously, following the reference vector (_Vref_), produced by the control system. However, because of the limitation of the switches in the inverter, it is not possible to covenant that any requested vector can be generated; as a matter of fact, only a limited number of vectors (27 vectors for three-level inverter) can be generated.

To overcome such difficulties, in any space vector modulation (SVM) scheme such as SVPWM and VSVPWM, the reference vector _Vref_ is generated by selecting the appropriate available vectors in each time mount in such a way that the mean of the applied vectors must be equal to the reference vector.

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**Fig. 1. Typical three-level inverter (a) structure of circuit, and (b) three-level inverter space vector diagram for balanced dc-link capacitors [6].**

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**Fig. 2. Equivalent circuit and capacitors current with two different short vector. (a) Short vector—100. (b) Short vector—211.**

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Equation (1) shows the mathematical relation between the timing of the applied vectors and the reference vector

\[
\begin{align*}
T_s V_{ref} &= \sum_{i=1}^{n} T_i \tilde{V}_i \\
T_s &= \sum_{i=1}^{n} T_i
\end{align*}
\]

where _Ts_ is the time frame and preferred to be as short as possible. It can be considered as a control
update period where an mean vector will be mathematically developed during this time duration. \( Ti \) is the corresponding time division for selected inverter vector _Vi and \( n \) is the number of applied vectors. Generally, the reference vector is produced by three different vector (\( n = 3 \)), and (1) can be converted to three different equation with three variables \( T1, T2 \), and \( T3 \) to be calculated. Many vector PWM techniques presented in [6], [7], [9]–[11], and [13]–[15] applying same technique of timing calculation. Fig. 1(b) shows the space vector diagram of a three-level inverter for balanced dc-link capacitors [6]. It is trum up of 27 switching states, from which 19 different voltage vectors can be selected. The number related with each vector in Fig. 1(b) shows the switching state of the inverter phases respectively. The voltage vectors can be classify into five groups, in relation to their amplitudes and their effects on different capacitor voltages from the view of the inverter ac side. They are six long vectors (200, 220, 020, 022, 002, and 202), three zero vectors (000, 111, and 222), six medium vectors (210, 120, 021, 012, 102, and 201), six upper short vectors (211, 221, 121, 122, 112, and 212), and six lower short vectors (100, 110, 010, 011, 001, and 101).

For producing _Vref, when one of the choice (_Vi), is a short vector, then there are two choices that can be made which can generate exactly the same result on the ac side of the inverter in the three wire connection (if voltages are balanced). For instance, the short vector “211” will have the same effect as “100” on the ac side of the inverter. However, this selection will have different result on the dc side, as it will cause a different dc capacitor to be chosen for the transfer of power from or to the ac side, and a different capacitor will be charged or discharged depending on the switching states and the direction of the ac side current.

Fig. 3. General diagram of a grid connected three-wire three-level inverter.

In order to generate the ac-side waveform, the vector diagram of Fig. 1(b) is used, where the dc capacitor voltages are presumed to be balanced. Fig. 1(b) can then be used to control the appropriate vectors to be selected and to calculate their corresponding timing \( (Ti) \) for developing the required reference vector based on the equation given in (1). Although the control system is trying to assure balanced capacitor voltages, should any unbalance occur during a transient or an abnormal operation, the above method will produce an inaccurate ac-side waveform which can be different from the original requested vector by the control system. This can result in the generation of even-harmonics, unbalanced current and unexpected dynamic behavior.

However, in some applications, the requirement of having balanced capacitor voltages may be too opposed. It is possible to work with either balanced or unbalanced capacitor voltages. The method proposed in this paper is based on the freedom of having balance or unbalanced capacitor voltages. In such applications, it is important to be able to generate an accurate reference vector based on (1), irrespective of whether the capacitor voltages are balanced or not, to achieve the desired objectives of the system.

C. Unbalanced Capacitor Voltages

Fig. 3 shows a traditional structure of a grid-connected three level inverter showing the dc and ac sides of the inverter. The dc-side system, shown as “N” can be composed of many circuit configurations, depending on the application of the inverter. For example, the dc-side system can be a solar PV, a wind generator with a rectifying circuit, a battery storage system or a merging of these systems where the dc voltage across each capacitor can be different or equal. One of the main ideas of this paper is to have an overall view of the switching effects on a three-wire connection of a three-level NPC inverter with a merging of these systems on the dc side.

Mathematically, in a three-wire connection of a two-level inverter, the \( dq0 \) field, \( v_d \), \( v_q \), and \( v_0 \) of the inverter in vector control can be considered as having two degrees of flexibility in the control system; because the zero sequence voltage, \( v_0 \) will have no effect on the system bearing in both the dc and the ac side of the inverter. However, in the three-level three-wire application illustrated in Fig. 3, with fixed \( v_d \) and \( v_q \) although \( v_0 \) will have no effect on the ac-side behavior, it can be useful to take advantage of \( v_0 \) to provide a new degree of freedom to control the sharing of the capacitor voltages in the dc bus of the inverter. By doing this, it is now possible to operate and control the
inverter under both balanced and unbalanced capacitor voltages while continuing to generate the correct voltages in the ac side. This characteristic is particularly useful in applications where the two capacitor voltages can be different, such as when connecting two PV modules with different MPPT points, or connecting a PV module across the two capacitors and including battery storage at the midpoint of the two capacitors, or connecting battery storage to each of the capacitors with the capacity to transfer different power from each battery storage.

**D. Effect of Unbalanced Capacitor Voltages on the Vector Diagram**

In the vector diagram shown in Fig. 1(b), capacitor voltage unbalance causes the short and medium vectors to have different magnitudes and angles compared to the case when the capacitor voltages are balanced. Fig. 4 shows the differences between two cases as spot in the first sector of the sextant in Fig. 1(b) for \( V_{C1} < V_{C2} \). Vector related to the switching state \(_{VI}\) can be calculated as follows [20]:

\[
\vec{V}_I = \frac{2}{3} \left( V_{aN} + aV_{bN} + a^2 V_{cN} \right) \tag{2}
\]

where \( a = e^{i(2\pi/3)} \) and \( V_{aN}, V_{bN} \) and \( V_{cN} \) are the voltage values of each phase with reference to “N” in Fig. 1(a). Assuming that the length of the long vectors \((2/3)V_{dc}\) is 1 unit and the voltage of capacitor \( C1, V_{c1} = hV_{dc} \), for \( 0 \leq h \leq 1 \), then the vectors in the first sector can be calculated using (2) and the results are given in (3)–(9).

\[
\vec{V}_{sd1} = h \tag{3}
\]
\[
\vec{V}_{su1} = 1 - h \tag{4}
\]
\[
\vec{V}_{l1} = 1 \tag{5}
\]
\[
\vec{V}_{l2} = \frac{1}{2} + \frac{\sqrt{3}}{2} j \tag{6}
\]
\[
\vec{V}_{sd2} = h \left( \frac{1}{2} + \frac{\sqrt{3}}{2} j \right) \tag{7}
\]
\[
\vec{V}_{su2} = (1 - h) \left( \frac{1}{2} + \frac{\sqrt{3}}{2} j \right) \tag{8}
\]
\[
\vec{V}_{m1} = \left( 1 - \frac{h}{2} \right) + h\frac{\sqrt{3}}{2} j. \tag{9}
\]
now have a different effect on both the dc and ac side.

Traditionally, each pair of short vectors is considered to be redundant, as the selection of any of the short vectors at any instance will have the same effect on the ac side. However, when the two capacitor voltages are different, the short vectors cannot be considered to be redundant any more. Thus, when \( h = 0.5 \), each different short vector needs different timing to generate the requested vector based on (1).

E. Selecting of Vectors and Their Effects on the AC Side of Inverter

To produce a reference vector based on (1), different combinations can be implemented. Fig. 5 shows different possible vector selections to produce a reference vector \( (\_V \ast) \) in the first sector based on the selections of different short vectors. For instance, to generate \( (\_V \ast) \) based on Fig. 5(a), one of following combinations can be selected with proper timing based on (1). The combinations are: \((221–210–100), (221–220–100), (221–200–100), (221–200–Zero), (000–220–Zero), (220–200–Zero)\), where “Zero” can be “000” or “111” or “222”. This explains that there is flexibility in choosing the correct vector selections. While all of these selections with suitable timing can generate the same reference vector, they have different affects on the dc and ac side of the inverter in their instantaneous behavior.

To investigate the ac-side behavior, the accuracy of the generated voltage must be examined. As far as the ac side is concerned, ideally the requested voltage \( _V \ast (t) \) should be exactly and simultaneously generated in the three phases of the inverter to have the correct instantaneous current in the ac side of the system. However, because of the limitation of the inverter to generate the exact value of the requested current in each phase, in the short time \( Ts \), only the average value of the requested vector \( _V \ast \) for the specified time window of \( Ts \) can be generated.

To investigate the continuous time behavior of the ac-side voltages, the error vector \( \_e (t) \) can be determine in order to determine how far the generated voltage deviates from the requested vector as follows:

\[
\_e(t) = V^*(t) - V_{spl}(t) \tag{10}
\]

\[
E(t) \triangleq \left| \int_0^t \_e(t) dt \right| ; \quad 0 \leq t \leq Ts \tag{11}
\]

where \( _{V_{apl}}(t) \) is the applied vector at the time “\( t \)”. This error can result in harmonic current across the impedance connected between the inverter and the grid. If this impedance is an inductor then the ripple in the inductors current \( _{IrL} \) can be expressed as

\[
\_I_{rL} = 1/L \int_0^t \_e(t) dt \tag{12}
\]

where \( \_e(t) \) is defined as

\[
\_e(t) \triangleq L \frac{d\_I_{rL}}{dt} . \tag{13}
\]

To derive (13), it is presume that the requested vector \( _V \ast (t) \) will produce sinusoidal current in the inductor, which is normally acceptable in the continuous time bearing of the system. Based on (11) and (12), the absolute value of error \( E(t) \) is directly related to the magnitude of the inductors current ripple. Although based on (1) and (11), \( E(Ts) = 0 \) or the sum of errors during the period \( Ts \) is zero; but to reduce the magnitude of high frequency ripples, it is important to minimize the error at each time instant. To achieve this, the three nearest vectors (TNV) are usually used. For example, in Fig. 5(a), to generate the requested vector \( _V \ast \), in the TNV method, the group \((221, 210, 100, 2011)\) appears to be the best three nearest vectors to be chosen.

Also, to reduce \( E(t) \), a smart timing algorithm for each vector in the TNV method has been proposed, such as dividing the time to apply each vector into two or more shorter times. However, this will have the effect of increasing switching losses. Dividing by two is common, acceptable solution. Moreover, reducing \( Ts \) will reduce the error \( E(t) \) while improving the accuracy of the requested vector generated by the control system. According to the basic rule of digital control, accuracy of the requested vector calculation can be improved by reduction of the sampling time and the vector determining time.

F. Selecting of Vectors and Their Effects on DC Side of the Inverter

As far as the dc side is concerned, different vectors have different result on the capacitor voltages which depend on the sum of the incoming currents from the dc side and the inverter side.

Fig. 3 shows \( ip, io \) , and \( in \) as dc-side system currents which are dependent on the dc-side system circuit topology and capacitor voltages. The currents coming from the inverter are related to the inverter switching and the ac side of inverter currents which can be
directly affected by the implemented vectors in the inverter. Selecting different vectors will transfer ac-side currents and power differently to the capacitors as discussed in Section II-B.

The instantaneous power transmitted to the dc side of the inverter from the ac side can be calculated as follows:

\[ p(t) = v_{Ia}i_a + v_{Ib}i_b + v_{Ic}i_c \]  

where \( v_{Ia}, v_{Ib}, \text{ and } v_{Ic} \) are the ac-side inverter instantaneous voltages with reference to the “\( N \)” point, and \( i_a, i_b, i_c \) are inverter currents.

For example, in the first sector of the vector diagram shown in Fig. 4, \( p(t) \) for the short vectors can be expressed by the following equations:

\[ \begin{align*}
\begin{aligned}
p_{211}(t) &= (1-h)V_{dc}i_a \\
p_{100}(t) &= hV_{dc}i_a \\
p_{221}(t) &= (1-h)V_{dc}i_c \\
p_{110}(t) &= hV_{dc}i_c.
\end{aligned}
\end{align*} \]

Ignoring the dc-side system bearing, selecting the upper short vectors, “211” and “221,” will affect the upper capacitor voltage, and selecting the lower short vectors, “100” and “110,” will affect the lower capacitor voltage. For example, when \( i_a > 0 \), if vector “211” is selected, it will charge the upper capacitor without any effect on the lower capacitor voltage and if vector 100 is selected, it will discharge the lower capacitor without having any effect on the upper capacitor voltage. By using (15) and (16), the rate of charging and discharging and their dependency on \( h \) and \( V_{dc} \) values and inverter currents can also be observed. However, for accurate investigations, the dc side system behavior needs to be considered in the control of charging and discharging rates of the capacitor voltages.

### III. PROPOSED TOPOLOGY TO INTEGRATE SOLAR PV AND BATTERY STORAGE AND ITS ASSOCIATED CONTROL

#### A. Proposed Topology to Integrate Solar PV and Battery Storage Using an Improved Unbalanced DC Functionality of a Three-Level Inverter

Based on the discussions in Sections I and II, two new configurations of a three-level inverter to integrate battery storage and solar PV shown in Fig. 6 are proposed, where no extra converter is required to connect the battery storage to the grid connected PV system. These can reduce the cost and improve the overall efficiency of the whole system particularly for medium and high power applications.

![Fig. 6. Proposed configurations for integrating solar PV and battery storage: (a) basic configuration; (b) improved configuration.](image-url)

Fig. 6(a) shows the diagram of the traditional configuration. In the proposed system, power can be transferred to the grid from the non-conventional energy source while allowing charging and discharging of the battery storage system as requested by the control system. The proposed system will be able to control the sum of the capacitor voltages \((V_{C1} + V_{C2} = V_{dc})\) to achieve the MPPT condition and at the same time will be able to control independently the lower capacitor voltage \((V_{C1})\) that can be used to control the charging and discharging of the battery storage system. Further, the output of the inverter can still have the correct voltage waveform with low total harmonic distortion (THD) current in the ac side even under unbalanced capacitor voltages in the dc side of the inverter.

Although this configuration can operate under most conditions, however when the solar PV does not produce any power, the system cannot work properly with just one battery.

Fig. 6(b) shows the improved configuration where two batteries are now connected across two capacitors through two relays. When one of the relays is closed and the other relay is open, the configuration in Fig. 6(b) is similar to that in Fig. 6(a) which can charge or discharge the battery storage while the renewable energy source can generate power. However, when the non-conventional energy is unavailable, both relays can be closed allowing the dc bus to transfer or absorb active and reactive power to or from the grid. It
should be noted that these relays are selected to be ON or OFF as required; there is no PWM control requirement. This also provides flexibility in managing which of the two batteries is to be charged when power is available from the non-conventional energy source or from the grid. When one of the batteries is fully charged, the relay connected to this battery can be opened while closing the relay on the other battery to charge. Special consideration needs to be made to ensure that current through the inductor $L_{\text{batt}}$ must be zero prior to opening any of these relays to avoid disrupting the inductor current and also to avoid damaging the relay.

Fig. 7. Control system diagram to integrate PV and battery storage.

### B. Control Topology

In Fig. 6(b), three different relay configurations can be obtained: 1) when the top relay is closed; 2) when the bottom relay is closed; and 3) when both relays are closed. Fig. 7 shows the block diagram of the control system for configuration 1). In Fig. 7, the requested active and reactive power generation by the inverter to be transferred to the grid will be calculated by the network supervisory block. This will be achieved based on the available PV generation, the grid data, and the current battery variables.

The MPPT block determines the requested dc voltage across the PV to achieve the MPPT condition. This voltage can be calculated by using another control loop, with slower dynamics, using the measurement of the available PV power. The details of the MPPT algorithm to determine the desired voltage ($V^{*}_{dc}$) can be found in [3] and [4].

Based on the requested active ($p^{*}$) and reactive power ($q^{*}$), and the grid voltage in the $dq$-axis, $v_{sd}$ and $v_{sq}$, the requested inverter current in the $dq$-axis, $i_{d}$ and $i_{q}$ can be obtained using (17):

$$
\begin{align*}
    p &= v_{sd}i_{d} + v_{sq}i_{q} \\
    q &= v_{sq}i_{d} + v_{sd}i_{q}
\end{align*}
$$

By using a proportional integral and derivative (PID) controller and decoupling control structure, the
inverter requested voltage vector can be calculated. The proposed control system is shown in Fig. 7. In the proposed system, to transfer a specified amount of power to the grid, the battery will be charged using surplus energy from the PV or will be discharged to support the PV when the available energy cannot support the requested power. After evaluating the requested reference voltage vector, the appropriate sector in the vector diagram can be determined. To determine which short vectors are to be selected, the relative errors of capacitor voltages given in (18) and (19) are used

\[
\varepsilon V_{c1} = \frac{V_{c1}^* - V_{C1}}{V_{C1}} \quad (18)
\]

\[
\varepsilon V_{c2} = \frac{V_{c2}^* - V_{C2}}{V_{C2}} \quad (19)
\]

where \( V^* \) and \( V \) are the desired capacitor voltages, and \( V_{C1} \) and \( V_{C2} \) are the actual capacitor voltages for capacitor \( C1 \) and \( C2 \), respectively.

The selection of the short vectors will determine which capacitor is to be charged or discharged. To determine which short vector must be selected, the relative errors of capacitor voltages and their effectiveness on the control system behavior are important. A decision function “\( F \)” as given in (20), can be defined based on this idea

\[
F = G_1 \varepsilon V_{c1} - G_2 \varepsilon V_{c2} \quad (20)
\]

where \( G1 \) and \( G2 \) are the gains associated with each of the relative errors of the capacitor voltages.

\( G1 \) and \( G2 \) are used to determine which relative error of the capacitor voltages is more important and consequently allows better control of the chosen capacitor voltage. For example, for an application that requires the balancing of the capacitor voltages as in traditional three-level inverters, \( G1 \) and \( G2 \) must have the same value with equal reference voltage values, but in the proposed application where the capacitor voltages can be unbalanced, \( G1 \) and \( G2 \) are different and their values are completely dependent on their definitions of desired capacitor voltages. By using \( V \) \( C2 = V \) \( dc - VC1 \) and \( V \) \( C1 = VBAT \) and selecting \( G2 \) much higher than \( G1 \), the PV can be controlled to the MPPT, and \( C1 \) voltage can be controlled to allow charging and discharging of the battery.

In each time step, the sign of \( F \) is used to determine which short vectors are to be chosen. When \( F \) is positive, the short vectors need to be selected that can charge \( C1 \) or discharge \( C2 \) in that particular time step by applying (14) and using similar reasoning to (15) and (16). Similarly, when \( F \) is negative, the short vectors need to be selected that can charge \( C2 \) or discharge \( C1 \) in that particular time step.

Based on the control system diagram given in Fig. 7, on the ac side, the requested active power, \( P^* \), and reactive power, \( q^* \), will be generated by the inverter by implementing the requested voltage vector and applying the proper timing of the applied vectors. Further, on the dc side, MPPT control can be achieved by strict control of \( VC2 \) \( (G2 - G1) \) with reference value of \( (V \) \( * \) \( dc - VC1) \) and more flexible control of \( VC1 \) with reference value of the battery voltage, \( VBAT \). By using the decision function \( F \) with the given reference values, the proper short vectors to be applied to implement the requested vector can be determined. With MPPT control, the PV arrays can transfer the maximum available power (PPV), and with generating the requested vector in the ac side, the requested power \( P^* \) is transferred to the grid. Then, the control system will automatically control \( VC1 \) to transfer excess power \( (PPV - P^*) \) to the battery storage or absorb the power deficit \( (P^* - PPV) \) from the battery storage.

The same control system is applicable for configuration 2) by changing the generated reference voltages for the capacitors. Configuration 3) represents two storage systems connected to grid without any PV contribution, such as at night when the PV is not producing any output power.

IV. SIMULATION AND VALIDATION OF THE PROPOSED TOPOLOGY AND CONTROL SYSTEM

Simulations have been carried out using MATLAB/Simulink to verify the effectiveness of the proposed topology and control system. An \( LCL \) filter is used to connect the inverter to the grid. Fig. 8 shows the block diagram of the simulated system. Three, series-connected PV modules are used in the simulation. The mathematical model of each of the PV units is given in (21) [21] and used in the simulation.
where \( I_{SC} \) is the short circuit current of the PV.

In the simulation, it is assumed that \( I_{SC} \) will change with different irradiances. With a solar irradiation of 1000 W/m\(^2\), \( I_{SC} \) is equal to 6.04 A and the open circuit voltage of the PV panels will be equal to \( V_{OC} = 44V \). The main parameters of the simulated system are given in Table I.

As discussed in Section III-B, \( G_2 \) must be much more than \( G_1 \) in order to achieve the MPPT condition and to have the flexibility to charge and discharge of the battery. Based on our experiments, any value more than 100 is suitable for this ratio. On the other hand, because the ratio of \( G_2/G_1 \) will only affect the short-vector selection, increasing this ratio will not affect other results. This value has been selected to be 200 to have good control on \( V_{dc} \), as shown in Table I.

The role of \( L_{BAT} \) is to smooth the battery current, especially in the transient condition. A wide range of values are acceptable for the inductor value, however, decreasing its value will increase the current overshoot of the battery. Also, its value is dependent of its adjacent capacitor value and its transient voltages. Due to the practical considerations (such as size and cost), the value of \( L_{BAT} \) is preferred to be low and has been chosen to be 5 mH based our simulation studies.

The values of \( K_p \), \( K_i \) and \( K_d \) are selected by modeling the system in the \( dq \)-frame. The current control loop can be converted to a simple system after using the decoupling technique shown in Fig 7. The details of this method can be found in [22].

It is assumed that the solar irradiation will produce \( I_{SC} = 5.61 \) A in the PV module according to (21). The MPPT control block, shown in Fig. 7, determines the requested PV module voltage \( V_{p} * \ dc \), which is 117.3 V to achieve the maximum power from the PV system that can generate 558 W of electrical power. The requested active power to be transmitted to the grid is initially set at 662W and is changed to 445W at time \( t = 40 \) ms and the reactive power changes from zero to 250 VAr at time \( t = 100 \) ms.

Fig. 9 shows the results of the first scenario simulation Fig. 9(a) and (b) shows that the proposed control system has correctly followed the requested active and reactive power, and Fig. 9(c) shows that the PV voltage has been controlled accurately (to be 177.3 V) to obtain the maximum power from the PV module. Fig. 9(d) shows that the battery is discharging when the grid power is more than the PV power, and it is charging when the PV power is more than the grid power. Fig. 9(d) shows that before time \( t = 40 \) ms, the battery discharges at 1.8 A since the power generated by the PV is insufficient. After time \( t = 40 \) ms, the battery current is about –1.8 A, signifying that the battery is being charged from the extra power of the PV module. Fig. 9(e) shows the inverter ac-side currents, and Fig. 9(f) shows the grid-side currents with a THD less than 1.29% due to the LCL filter. The simulation results in Fig. 9 show that the whole system produces a very good dynamic response.

Fig. 10 shows the inverter waveforms for the same scenario. Fig. 10(a) shows the line-to-line voltage \( V_{ab} \), and Fig. 10(b) shows the phase to midpoint voltage of the inverter \( V_{ao} \). Fig. 10(c) and (e) shows \( V_{ao}, \) \( V_{on}, \) and \( V_{an} \) after mathematical filtering to determine the average value of the PWM waveforms.
VI. CONCLUSION

In this paper integration and operation of a three-level neutral-point-clamped (NPC) inverter maximum power point trackers (MPPTs) for dc-ac distribution applications has been designed and implemented. The inverter controls the power flow between dc bus and ac grid, and controls the dc bus to a certain range of voltages. A novel regulation mechanism according to the inductor current levels has been proposed to balance the power flow and accommodate load variation. A new control algorithm for the proposed system has also been presented in order to control power flow between solar PV, battery, and grid system, while MPPT operation for the solar PV is achieved simultaneously. The effectiveness of the proposed theory and control algorithm was tested using simulations and results are presented.

REFERENCES


