Hybrid PV/wind system with quinary asymmetric inverter without increasing DC-link number

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Abstract This paper suggests quinary asymmetric inverter with coupled inductors and transformer, and uses it in hybrid system including photovoltaic (PV) and wind. This inverter produces twenty-five-level voltage in addition to merits of multilevel inverter, has only one DC source. Then, it is adequate for hybrid systems, which prevents increasing DC-link and makes control of system easy. Proposed structure also provides isolation in the system and the switch numbers are reduced in this topology compared with other multilevel structures. In this system, battery is used as backup, where PV and wind have complementary nature. The performance of proposed inverter and hybrid system is validated with simulation results using MATLAB/SIMULINK software and experimental results based PCI-1716 data acquisition system.

1. Introduction

In recent years, renewable energies were expanded because of fossil fuel consumption and greenhouse-effect gas emission [1–3]. Research and development efforts in renewable energies are required to accurately predict their output reliably assembling them with other conventional sources. So, use of battery in such systems is beneficial solution for increase of reliability and better operation of those systems. Meanwhile, hybrid system including different types of renewable energies was proposed [4,5]. Hybrid system in addition to advantages of renewable energies, causes reduction in battery size and increase in reliability of system [6,7]. The renewable energies in hybrid system can be photovoltaic (PV), wind, fuel cell, etc. In this paper, PV and wind systems are used because of complementary operation. In hybrid systems, an inverter between DC link and load provides ac voltage demand of load, which may have various types.

Nowadays, multilevel inverters receive more attention [8–10], which include some power semiconductors and DC voltage sources. The most common multilevel inverter topologies are the cascaded, diode-clamped, and capacitor-clamped types [11–13]. Multilevel inverters with only one DC source
may be the most desirable topology. Recently [14] presented an inverter called a five-level-active-neutral-point-clamped with coupled inductor, which uses split of the DC-link capacitor. In [8] inverter was proposed using coupled inductors. This inverter can output a novel, single phase, five-level voltage with only one DC source. Meanwhile, asymmetric structures use geometric progression for voltage of DC sources to increase the output levels. Then, it is desirable to use of new inverters in asymmetric structures for producing more voltage levels in output. But increasing DC source numbers in asymmetric structures causes cost increase; also control of system with more DC links is more complex.

This paper proposes quinary asymmetric inverter with coupled inductors and transformer, and uses it in hybrid system including PV and wind systems. This inverter has one DC source which makes it easy and usable in hybrid system. Theoretical analysis and simulation and experimental results are presented to show the validity of the proposed inverter and proposed hybrid system.

2. Renewable energy systems

2.1. PV system

PV system is based on solar energy, where PV cell is the most basic generation part in PV. As Fig. 1(a) shows, the PV cell is formed from a diode and a current source was connected anti-parallel with a series resistance [15–17].

The relation of the current and voltage in the single-diode cell can be written as follows:

\[
I_{PV} = I_{ph} - I_D \exp \left( \frac{q(V_{PV} + R_{Ser} I_{PV})}{AKT} \right) - 1
\]

(1)

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where $I_{PV}$ and $V_{PV}$ are the current and voltage of PV cell respectively. And, $I_{ph}$ is photocurrent, $I_0$ is diode saturation current, $T$ is cell temperature, $K$ is Boltzmann’s constant, $q$ is coulomb constant, $A$ is P–N junction ideality factor, and $R_{mod}$ is series resistance. Photocurrent is directly proportional to solar irradiation and cell temperature, which is described as

$$I_{ph} = I_{sc} + k_i(T - T_r)(G/G_r)$$

(2)
Several same PV cells are arranged together in parallel and series to form PV modules. This work is performed in order to increase output voltage and current of PV system. The current versus voltage of the PV module can be formulated as

\[
I_{PV} = \frac{N_p I_{ph}}{C_0} - N_p I_o \exp \left( \frac{q(V_{PV} + R_{mod} I_{PV})}{N_s A K T} \right) - 1
\]  

Fig. 1(b) shows PV modeling of module, where \(N_p\) and \(N_s\) are number of the parallel and series PV cell, respectively.

For each module, two characteristic curves are defined: voltage–current (\(V–I\)) and voltage–power (\(V–P\)). These curves are plotted based on solar irradiance and temperature. Fig. 2 shows such curves for typical PV module. From Fig. 2, it is obvious that in each solar irradiance and temperature, the voltage, current, and power can have different mounts. But there is one point with specific voltage and current which produced maximum power [15]. This point is known as maximum power point (MPP), and operation in it is known as maximum power point tracking (MPPT).

2.2. Wind system

The mechanical power of a wind turbine is expressed as follows [18–20]:

\[
P_{mech} = \frac{1}{2} \rho A r C_p V_w^3
\]  

where \(\rho\) is the air density, \(A_r\) is the area swept out by the turbine blades, \(V_w\) is the wind velocity, and \(C_p\) is the power
Figure 9  Control loop of load voltage in hybrid system.

Table 2  Inverter parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{DC}$</td>
<td>100 V</td>
</tr>
<tr>
<td>$L_{11} = L_{12} = L$</td>
<td>3.1 mH</td>
</tr>
<tr>
<td>$M$</td>
<td>3 mH</td>
</tr>
<tr>
<td>Nominal frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Load resistance</td>
<td>20 Ω</td>
</tr>
<tr>
<td>Load inductance</td>
<td>8.3 mH</td>
</tr>
</tbody>
</table>

Figure 10  Output voltage of proposed inverter with respect to time(s); (a) upper unit; (b) lower unit; (c) total.
Coefficient and represents the efficiency of the wind turbine which is expressed as

\[ C_{p}(\lambda, \beta) = 0.5176 \left( \frac{116}{\lambda} - 0.4\beta - 5 \right) e^{\left( \frac{-2}{\lambda^2} \right)} + 0.006\lambda \]  \hspace{1cm} (5)

\[ \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta - \frac{0.035}{\beta^3 + 1}} \]  \hspace{1cm} (6)

where \( \lambda \) is tip speed ratio, \( \beta \) is blade pitch angle (deg), \( R \) is the blade radius (m), and \( \omega \) is the rotational speed (rad/s). The torque obtained from wind energy is transferred via the turbine/generator shaft to the rotor of the generator and drives the electrical generator, and in this paper the permanent magnet synchronous generator (PMSG) is used in the output of wind turbine.
Figure 13 MPPT operation of each PV module in hybrid system.

Figure 14 Wind system characteristics; (a) power characteristic curve of the wind turbine; (b) wind speed variation with respect to time(s).
The power characteristic curve of a typical wind turbine is shown in Fig. 3. It is observed that the maximum power output occurs at different turbine speeds for different wind velocities.

3. Proposed hybrid system

3.1. Proposed quinary asymmetric inverter with coupled inductors and transformer

Single-phase five-level inverter with coupled inductors and one DC source was first proposed in [6], which is presented in Fig. 4. In this structure no split of the DC capacitor is needed, avoiding the voltage balancing. The level of the output voltage is half of the DC voltage in all switching conditions, causing much reduced \( \frac{dv}{dt} \). In this inverter, the voltage stresses on all the switches are the same. So, construction of it is easy.

In Fig. 4, \( 2E \) is the DC source voltage and \( L_{11} \) and \( L_{12} \) are the two coupled inductors. Two coupled inductors have the same number of turns and the mutual inductance of them is \( M \). With attention to Fig. 4 and assuming \( L_{11} = L_{12} = L \), the voltage of coupled inductors can be derived as follows:

\[
L \frac{di_b}{dt} - M \frac{di_c}{dt} = v_{bn} - v_{2n}
\]

(7)

\[
L \frac{di_c}{dt} - M \frac{di_b}{dt} = v_{cn} - v_{2n}
\]

(8)

And according to Kirchhoff’s current law, the following is obtained:

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Hybrid system parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load voltage</td>
<td>220 V</td>
</tr>
<tr>
<td>Load amount</td>
<td>( Z_1 = 35 + 5j )</td>
</tr>
<tr>
<td></td>
<td>( Z_1 = 30 + 20j )</td>
</tr>
<tr>
<td></td>
<td>( Z_1 = 26 + 25j )</td>
</tr>
<tr>
<td>Nominal frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Filter capacitance</td>
<td>30 ( \mu F )</td>
</tr>
<tr>
<td>Filter inductance</td>
<td>0.5 mH</td>
</tr>
</tbody>
</table>
\[ i_b + i_c + i_L = 0 \]

From (7-9), \( v_{2n} \) can be expressed as

\[ v_{2n} = v_{2n} + v_{cn} + \left( L - M \right) \frac{\partial i_L}{\partial t} \]

\[ v_{2n} = \frac{v_{bn} + v_{cn}}{2} \]

The leakage inductance can be designed to be near to mutual inductance of two inductors. Therefore, (10) can be rewritten as

\[ v_{2n} = \frac{v_{bn} + v_{cn}}{2} \]
From Fig. 4 and (11), the output voltage of the inverter is obtained:

\[
v_{12} = v_{1n} - v_{2n} = v_{1n} - \frac{(v_{1n} + v_{on})}{2}\quad (12)
\]

So, the output voltage can have five levels, which are summarized in Table 1. Then, it is obvious that the switching state of \(S_1\) is decided by the sign of \(v_{12,ref}\) (the reference of \(v_{12}\)):

\(S_1 = 1\) if \(v_{12,ref} \geq 0\) and \(S_1 = 0\) if \(v_{12,ref} < 0\), which is very easy to implement. However, the switching states of \(S_3\) and \(S_5\) cannot be selected without careful study [8]. To decide the switching states of \((S_3, S_5)\), the following PWM algorithm is presented:

The dwelling time for the switch switches within every sample time, and \(T_s\) is defined as follows:

\[
T_{dwell} = \frac{|v_{12,ref}|}{K v_I}
\quad (13)
\]

where the integer \(K\) is calculated by

\[
K = \left\lceil \frac{|v_{12,ref}|}{v_I} \right\rceil
\quad (14)
\]

The function \([x]\) rounds \(x\) to the nearest integer less than \(x\). Obviously, the dwelling time in (13) can be generated using the conventional triangle wave which is shown in Fig. 5.

Asymmetric structures use geometric progression for DC source voltages to increase the output levels. Such a structure produces output voltage with summation of series structures voltages with different DC sources, which is displayed in Fig. 6.

Progression factor in quinary asymmetric structure is 5. So, the voltage of DC sources can be written as follows:

\[
V_i = (5^{i-1}) V_{DC}, \quad i = 1, 2, 3, \ldots, n
\quad (15)
\]

Then, maximum levels number which inverter can be generated is

\[
N_{ML} = 5^n
\quad (16)
\]

and, the maximum generated voltage of inverter can be obtained as

\[
V_{out, \text{max}} = \frac{1}{2} (5^n - 1) \frac{V_{DC}}{2}
\quad (17)
\]

According to a bow description, it is obtained that two series five-level inverter with quinary asymmetric structure creates twenty-five-level inverter. But, increasing DC sources number in quinary structure causes cost increase, also control of system with more DC links is more complex. Then use of transformer in the proposed structure is the solution of represented drawbacks. New proposed structure is shown in Fig. 7. From Fig. 7, two transformers have different turn ratios according to (15). Then, the turn ratio of first transformer is 1:1, and the turn ratio of second transformer is 1:5. Use of transformer in this structure, in addition to decreasing DC source number to one, causes reliability increase and isolation. Using coupled inductor in this structure causes switches number to reduce. Also, the voltage stresses on all the switches on each inverter section are the same. Then, the switching of two blocks of
proposed inverter is based on PWM, which is explained later, where each block is switched independently and based on output level.

3.2. Proposed hybrid system with proposed inverter

The configuration of hybrid system is shown in Fig. 8, where PV connected to the DC-link through the DC–DC converter and PMSG wind turbine is connected to the same DC-link through the diode rectifier and DC–DC converter, and also, battery is connected to it by DC–DC converter. Because of low voltage generated from PV and wind systems, the boost DC–DC converter is preferred. The boost converter of PV section does MPPT of PV system and, in wind section, the diode rectifier acts as the DC source, and its output is controlled by boost converter to apply MPPT of wind system. The battery

\begin{figure}[h!]
\centering
\includegraphics[width=\textwidth]{figure19.png}
\caption{Output parameters of the load with respect to time(s); (a) load voltage; (b) load power.}
\end{figure}
system is used as backup for unpredictable nature of PV and wind. But, in high DC-link voltage, it is necessary to series connection of multiple batteries and connecting them to DC-link. The other solution is use of bidirectional boost converter. This battery with its converter momentarily absorbs or injects excess power corresponding to abrupt change in the PV and wind systems. Then, an inverter between DC-link and load provides ac voltage demand of load. The inverter may have various types. In this paper, it is used from proposed 25-level inverter, where because of its multilevel nature, it has merits of multilevel inverter. Also, the presence of one DC source is very suitable for this hybrid system, where control of one capacitor voltage is very easy and does not have complexity of several capacitors voltage as source of multilevel inverter. This structure also provides isolation in the system. The control loop of hybrid system is presented in Fig. 9.

4. Simulation and experimental results

For investigating the proposed structure, results of system are studied. In this paper, the results include two sections: simulation and experimental as follows.

4.1. Simulation results

4.1.1. Proposed inverter

Inverter shown in Fig. 7 has been simulated by MATLAB/SIMULINK to verify proposed topology. The system parameters with RL load are listed in Table 2. Fig. 10 presents output voltage of the inverter.

4.1.2. Hybrid system with proposed inverter

The proposed hybrid system is simulated, and the results of it are expatiated as follows. Different MPPT algorithms have been developed. In this paper, the perturbation and observation (P&O) algorithm with the merit of simplicity is used. 4.1.2.1. PV system. In this paper, 10 numbers of 250 W PV module (in nominal condition of \( G = 1000 \text{ W/m}^2 \) and \( T = 25 \text{ °C} \)) are paralleled, where it is considered stepped variation for solar irradiance and temperature in Fig. 11. The output powers of PV system and DC–DC converter are shown in Fig. 12. From Fig. 12, it can be seen that there is difference between those powers, which is because of system losses. The boost converter increases PV voltage up to DC link level. MPPT operation of each PV module is presented in Fig. 13, where it is obvious that utilization of each PV module is almost in MPPT points.

4.1.2.2. Wind system. In this paper, the power characteristic curve of the wind turbine is shown in Fig. 14(a). The wind speed variation is assumed stepped according to Fig. 14(b). The rotor speed, output power of turbine, and delivered power to DC link are presented in Fig. 15.

4.1.2.3. Hybrid system. As represented, the output power of PV and wind systems is transferred to DC-link and then the DC-link power is delivered to load. The parameters of simulated system are listed in Table 3, where the load is unbalanced. Fig. 16 displays DC-link voltage which is fixed in 64 V, although unbalancing of the load causes little fluctuation in the voltage. In this system, the battery system is used and its voltage increases with bidirectional boost converter. The exchanged power between system and battery is shown in Fig. 17. If the exchanged power is positive, the battery system compensates deficiency of hybrid power, and if the exchanged power is negative, the excess power is stored in battery. Then, DC-link voltage is transmitted from inverter and delivered to ac load. The used inverter in this paper, as represented, is proposed quinary inverter with coupled inverters and transformer which generate 25-level voltage. Fig. 18 shows the phase voltage of proposed inverter in this system. The load voltage and power are displayed in Fig. 19. Also, Fig. 20 shows correct MPPT operation of wind system.
4.2. Experimental results

Base segment of proposed inverter according to Fig. 4 was built using IRFP460 MOSFETS as the switching devices and MUR820G as fast diodes in this topology. A DC voltage source with amplitude 12 (V) was used to individually supply the inverter. The switching signals that were obtained from PWM algorithm were produced with PCI-1716 DAQ. The switching signals were interfaced with the inverter power switches through driver TLP250. Fig. 21(a) shows photographs of the prototype. The load voltage of the inverter is shown in Fig. 21(b). Measured five levels are 0, ±6, ±12. Load voltage total harmonic distortion (THD) was measured with power analyzer and it is about 38.2%.

5. Conclusion

This paper proposes hybrid system including PV and wind systems suggested quinary asymmetric inverter with coupled inductors and transformer. This inverter outputs twenty-five-level voltage with only one DC source. This structure has such merits as easy control and isolation, and uses battery system backup, where PV and wind have complementary nature. The simulation results showed that the proposed inverter
produces a high-quality load voltage and it demonstrates its ability in hybrid system. Also, the experimental results verified the proportionality of proposed inverter.

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References


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