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Standalone Micro grid with Five-Level Diode Clamped Inverter Based Hybrid Generation System

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Abstract

This research introduces a novel design for independent microgrids that uses a 5-level diode clamped inverter (DCI) to connect hybrid power generators (HGS) to conventional electrical loads. By using photovoltaic (PV) arrays, battery banks, and diesel generators (DG) as independent dc sources for DCI, the HGS does away with the need of input capacitors for DCI and the accompanying voltage balancing. For the 2Vdc level of DCI output voltage, the DG and PV array and/or battery provide the load. If the voltage is Vdc, the load is similarly supplied by the PV array and/or battery. Equally, a different PV array, battery pack, and DG are used to power the -Vdc and -2Vdc levels. The battery may be charged by excess PV electricity if and when it becomes available. To the contrary, if the PV power is insufficient, the charged battery pack might help to supply the load. By incorporating DG, the system's dependability and capacity to function independently are improved. There is no longer any requirement for basic current extraction since synchronisation with the DG is not necessary. Different scenarios for running the proposed autonomous microgrids with 5-level DCI-based HGS are analysed.

Keywords

Microgrids, multilayer inverters, diode-clamped inverters, diesel generators, and solar PV systems are all discussed.

INTRODUCTION

Management of the energy supply for limited loads using dispersed generation located in the same area is what microgrids are all about [1]. Microgrids are predicted to play a major role in electric power production for both electrified and non-electrified rural regions [1] as a result of the widespread use of renewable energy technologies. Typically, villages are spread out, have small populations, and are situated in outlying areas. As a consequence, these areas often go without electricity owing to logistical, technological, and financial constraints. Access to reliable electric power has the potential to greatly boost rural communities' economic development and living conditions [2]. This has spurred the Indian government to launch a number of initiatives aimed at extending electricity service to the country's vast rural population. Because of developments in power electronics and signal electronics, power converters are now widely used, making renewable energy technologies commercially viable and gaining widespread support [3, 4]. Electric power may be generated using renewable energy sources to meet the localised demand. A freestanding microgrid is a system in which power electronic converters are used to independently generate, distribute, and consume electricity on a small scale without connecting to or being supported by a larger utility network. Solar energy has become one of the primary power sources for the microgrids in the tropics since it is free, clean, and plentiful [3]. It has widespread acceptance and a number of benefits, but its unpredictable nature is a key drawback [5]. This weakness means it can't be relied on to maintain a constant flow of electricity [6]. Therefore, it is generally stated that PV systems need battery backup to provide a constant power supply [6-12], despite the expensive expense of such a solution. Microgrids often include both renewable and traditional energy sources, as well as energy storage technologies [1].

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Because of this, a hybrid power system has emerged (HGS). According to Blackstone et al. [1], for microgrids to be both feasible and dependable, diesel generators (DG) must be used so that load demand may be met even when renewable energy sources are not available. DGs are an excellent energy source for off-grid microgrids because they provide enhanced power dependability, self-sufficiency, and independence from the weather. Microgrids have been claimed to utilise DG in references [5, 8-12]. Power electronic converters (PECs) play an important role in the power structure of standalone microgrids by acting as an interface between multiple energy sources, ESDs, and localised loads to ensure optimal control of unidirectional and bidirectional flow of power flow while adhering to the specifications of load, energy sources, and ESDs. A PEC (which may be a dc dc converter or rectifier) is linked to each of the ESDs and the load, and this PEC in turn is connected to a common voltage source inverter (VSI). It has been shown that 2-level VSIs occur in isolated microgrids that feed ac loads [1, 10, 12]. Lower output voltage distortion, lower dv/dt and voltage stress, enhanced power quality at the supply end, lower common mode voltages, etc. [13] are just a few reasons why multi-level inverters (MLIs) might be favoured over two-level inverters. According to Rodriguez et al. [13], many MLI topologies have been surveyed.

INDEPENDENT MICROGRID DESIGN

Where Vpv, Vbat, and Vdg are the terminal voltages of the PV array, battery pack, and DG; Ipv, Iinv, and Idg are the currents supplied by the PV array, VSI, and DG; Ppv, Pbat, and Pdg are the powers supplied by the PV array, battery pack, and DG; Vdc is the dc-link voltage; and Cdc is the dc-link capacitor. A PV panel provides the electricity for a standalone microgrid, and a dc-dc converter connects the panel to the dc connection. This converter regulates the current flowing from the PV array to the load, keeping the PV system running at its optimum efficiency. Using a bidirectional dc-dc converter, a battery pack is connected to the system's shared DC bus in order to store energy. By using this converter, the battery may be charged and discharged in a safe and measured manner. Because of their parallel connection at G1 and G2, VSI requires DG synchronisation. So that Iinv follows the core active component of Idg, the VSI is run in current controlled mode. Therefore, an algorithm for extracting basic current is required. While the sun is out, the PV panel can provide the power needs of the home.

The battery or DG may help the PV system fulfil the load demand if the PV system's output is inadequate. One of the first things that must happen is for the battery to provide enough power to satisfy the need. The DG would kick in to provide the load if the battery was depleted or couldn't provide enough power to satisfy the demand. If the PV power output is more than the load requirement, the difference may be utilised to charge the battery. Whenever the battery reaches its maximum capacity, the extra energy must be burned up in the fake load. This case does not call for the use of DG, since it is sitting idle. The PV panel is useless for generating electricity at times of low light intensity, such as at night. The load may be supplied by the charged battery through the bidirectional dc dc converter and VSI. In the unlikely event that the battery is unable to provide enough power, DG steps in to fill the void. If the battery dies, DG becomes more important since it can provide power by itself. As a result, DG may be used to guarantee a steady and consistent electric power supply, no matter the weather.

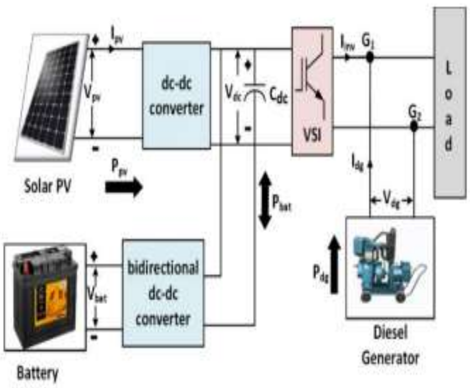

Fig. 1. General architecture of standalone microgrid with HGS.

PROPOSED DCI-BASED INDEPENDENT MICROGRID

The suggested 5-level DCI based HGS for freestanding microgrid is shown in block diagram form in Fig. 2. The three main components of this HGS system are the photovoltaic arrays (PV1 and PV2), the battery banks (B1 and B2), and the DGs (DG1 and DG2). Through separate dc-dc converters, PV1 and B1 are connected to create a shared dc-link with a voltage set to Vdc2. In order to provide both regulated charging and draining, B1 necessitated a bidirectional dc-dc converter. By connecting PV2 and B2 with individual dc-dc converters, a dc connection is produced, with a voltage level of Vdc3. PVES1 and PVES2 are two different configurations of photovoltaics (PV), batteries, and dc-dc converters. Unregulated rectification converts the alternating current (ac) voltages (Vdg1 and Vdg2) produced by DG1 and DG2 into direct current (dc) voltages (Vdc1 and Vdc4). Therefore, the 5-level DCI has access to Vdc1, Vdc2, Vdc3, and Vdc4 as input voltages, guaranteeing a regulated ac supply to the load. This new architecture for 5-level DCI uses six IGBTs (S1-S6) and four diodes (D1-D4). The voltage across each capacitor in a standard 5-level DCI is Vd/4 for a given input supply voltage of Vd. If you want everything to work as it should, you'll need to make sure the voltage across the input capacitor is consistent at all times. However, in the suggested topology, the four sources for 5-level DCI are DG1, PVES1, PVES2, and DG2, hence voltage balancing is unnecessary. Each of the five possible voltage outputs from the 5-level DCI is listed in Table I, along with the order in which the switches are flipped.

$V_{dc1}, V_{dc2}, V_{dc3}$

and Vdc4 are regulated by means of dc-dc converters or field excitation control at Vdc. The output voltage of DCI can attain five levels (zero, $\pm Vdc$, and $\pm 2Vdc$) for the corresponding switching states, as indicated in Table I. For the desired operation of proposed topology, input voltages to the 5-level DCI,

$V_{dc1}-V_{dc2}-V_{dc3}-V_{dc4}$, need to be equal (i.e. $V_{dc1}=V_{dc2}=V_{dc3}=V_{dc4}=V_{dc}$). In order to ensure this, the automatic voltage regulation (AVR) system controls the field excitation of DG1 and DG2, resulting in $V_{dc1}=V_{dc4}=V_{dc}$. PVES1 and PVES2 regulate Vdc2 and Vdc3, respectively. The duty cycles of dc-dc converters associated with PVEC1 and PVES2 are controlled so that Vdc2 and Vdc3 are regulated at Vdc. This leads to $V_{dc1}=V_{dc2}=V_{dc3}=V_{dc4}=V_{dc}$. PVEC1 and PVES2 is operate based on available PV power, load demand and battery pack capacity as discussed in Section-I. The charging and discharging of the battery pack are controlled by the bidirectional dc-dc converter. The details of mathematical modelling of PV cell, battery pack and 5-level DCI are provided in following sub-sections.

TABLE III. SWITCHING SEQUENCE OF 5-LEVEL DCI

State	Output Voltage Level	Switching Sequence					
		S1	S2	S3	S4	S5	S6
1	$2V_{dc}$	ON	ON	ON	OFF	OFF	OFF
2	V_{dc}	OFF	ON	ON	OFF	OFF	OFF
3	0	OFF	OFF	ON	OFF	OFF	OFF
4	$-V_{dc}$	OFF	OFF	OFF	ON	ON	OFF
5	$-2V_{dc}$	OFF	OFF	OFF	ON	ON	ON
6	0	OFF	OFF	OFF	ON	OFF	OFF

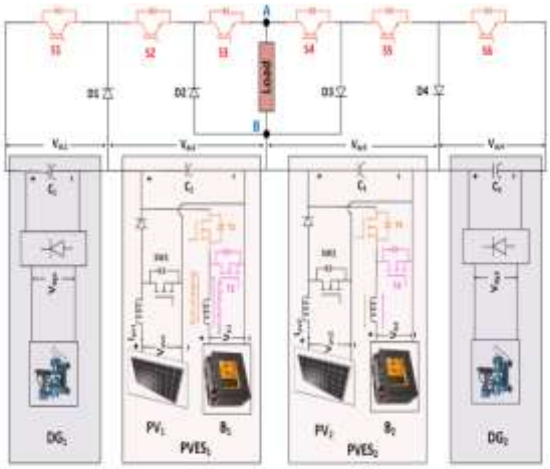

Fig. 2. Diagram of the proposed 5-level DCI based standalone microgrid

PV Cell Mathematical Modelling PV array is made up of a series and parallel arrangement of PV modules. PV cells are another component of these panels. As shown in Fig. 3, a PV cell's equivalent circuit consists of the photon current iph, the diode current iD representing the voltage-dependent current lost to recombination, the terminal current ipv, the terminal voltage Vpv, and the series resistance rs and the shunt resistance rp. The formula [3] describes the connection between iph, iD, ipv, and vpv

$$i_{pv} = i_{ph} - i_D - \frac{V_{pv}+r_s.I_{pv}}{r_p} \qquad (1)$$

.

Further, iD can be represented as [3]

$$i_D = i_{sat}.\left[e^{q.(V_{pv}+r_s.I_{pv})/A.k.T} - 1\right] \qquad (2)$$

where, $isat$ is the diode saturation current, q is the electrical charge, A is the diode ideality factor, k is the Boltzmann constant, and T is the temperature

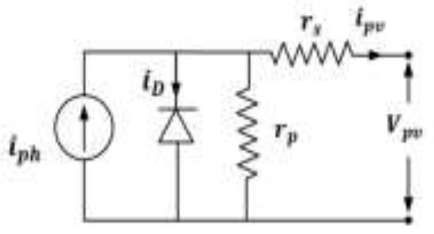

Fig. 3. Electrical equivalent circuit of single PV cell [3].

Modelling of battery system

There is still a preference for bigger capacity rechargeable lead-acid batteries due to their cheap cost. In (3), Vbt and Ecell represent the battery's terminal voltage and internal cell voltage, respectively; Ib represents the current delivered by the battery; and Rint represents the battery's internal resistance. Whereas discharging, Ecell > Vbt (due to the voltage drop across the battery's internal resistance) and Ib > 0 (due to the battery supplying the current), while while charging, Ib 0 (due to the current being provided by the charger) and Vbt > Ecell (as the charging current causes voltage drop across the internal resistance of the battery). According to [17], Ecell is a nonlinear function of the battery's state of charge (SOC), Ib, and the low frequency current dynamics.

$$V_{bt} = E_{cell} - I_b R_{int} \qquad (3)$$

OPERATING MODES OF STANDALONE MICROGRID

The proposed microgrid incorporates HGS interfaced with the ac loads through 5-level DCI. Depending on the load demand, atmospheric conditions and generation capability, different sources come into picture over the daily operation and full cycle of the ac supply. This section presents discussion on the operation of the proposed standalone micorgrid under five different operating modes, as defined in Table II, in the following subsections. During the Mode I–IV, the AVR controls the excitation of DG1 and DG2 to regulate Vdc1–Vdc4 at Vdc.

MODE-I

This mode is related to periods of high light intensity and considers that the power generated by PV and DG exactly match the load demand. This infers that the battery pack has no role to play in this mode. The battery pack is idle and takes no part in power transfer in terms of charging or discharging. The duty cycle of dc-dc converters, interfacing PV1 and PV2 with the respective dc-links, are controlled to ensure that Vdc2 and Vdc3 regulated at Vdc.

MODE-II

In this mode, along with the DGs and PVs, B1 and B2 also supply power to meet the load demand. This mode comes into effect when due to the low irradiance levels, the PV1 and PV2 cannot solely maintain Vdc2 and Vdc3, respectively. Hence, in order to meet the load demand the bidirectional dc-dc converters operate as boost converter to control the discharging of B1 and B2. The combination of PV1–B1 and PV2–B2 supply the necessary power to (i) regulate Vdc2 and Vdc3 at Vdc, and (ii) meet the load demand with the help of DG1 and DG2

MODE-III

When operating in Mode I or II, if the load is considerably reduced then the excess power would result in loss of regulation for Vdc2–Vdc3. Mode–III can solve this issue by changing the operation of bidirectional converters from boot to buck mode and facilitating the charging of B1–B2. Thus, the battery act as load and excess power generated by PV1 and PV2 are utilized for controlled battery charging. This charging action ensures that Vdc2–Vdc3 are maintained at Vdc, while ensuring that the light load demand is met. The charged battery can be used to support the load demand in case of Mode–II and IV.

MODE-IV

If B1 and B2 have sufficient charge, then at night or in absence of solar irradiance, they can support the load. B1 and B2 need to be charged during the daytime by operating the system in Mode–III. B1 and B2 will discharge accordingly as in Mode–II and regulate Vdc2–Vdc3 at Vdc. E. MODE-V Under no-load condition or if DG is unavailable due to maintenance requirement or some other issue, then the ac load is not supplied with electric power. If this occurs at night time or during the periods of low light intensity then PV1 and PV2 do not produce enough power for any sort of utilization. However, in such a scenario arises during day time then the generated electric energy available at the terminals of PV1 and PV2 can be utilized to charge B1 and B2, respectively. Depending on the load demand, battery and atmospheric conditions, one of the five modes can be activated.

TABLE II. DIFFERENT OPERATING MODES OF PROPOSED STANDALONE 5-LEVEL DCI BASED MICROGRID

Operating Modes	Energy Source						Energy Consumption		
	DG_1	$PVES_1$		$PVES_2$		DG_2	Load	B_1	B_2
		PV_1	B_1	PV_2	B_2				
MODE-I	YES	YES	NO	YES	NO	YES	YES	NO	NO
MODE-II	YES	YES	YES	YES	YES	YES	YES	NO	NO
MODE-III	YES	YES	NO	YES	NO	YES	YES	YES	YES
MODE-IV	YES	NO	YES	NO	YES	YES	YES	NO	NO
MODE-V	NO	YES	NO	YES	NO	NO	NO	YES	YES

TABLE III. PERFORMANCE OF THE STANDALONE MICROGRID WITH 5-LEVEL DCI BASED HGS

Operating Modes	Load (Ω)	Load Current (A)	Power Supplied (W)						Power Consumed (W)		
			DG_1	$PVES_1$		$PVES_2$		DG_2	Load	B_1	B_2
				PV_1	B_1	PV_2	B_2				
MODE-II	15	9	237	158	223	158	227	246	1249	-	-
MODE-III	26	4.22	143	402	-	402	-	145	750	172	170
MODE-IV	20	4.75	182	0	288	0	290	187	947	-	-

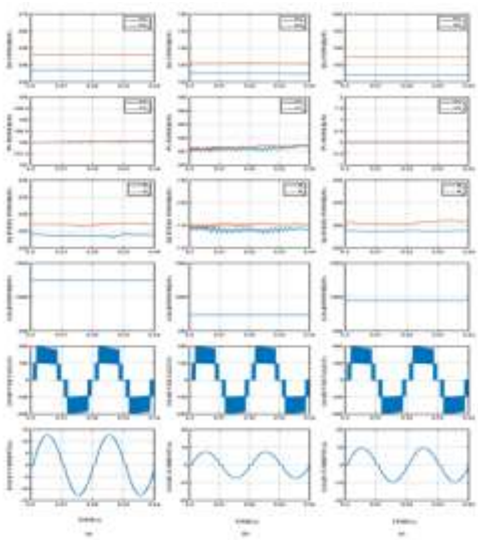

Fig. 4. (a) DG power, PV power, Battery pack power, Load power, Load voltage and Load current operating in Mode II, (b) DG power, PV power, Battery pack power, Load power, Load voltage and Load current operating in Mode III, and (c) DG power, PV power, Battery pack power, Load power, Load voltage and Load current operating in Mode IV

SIMULATION RESULTS

The proposed standalone microgrid with 5-level DCI based HGS is modeled on MATLAB/SIMULINK platform. The specifications of each energy source and storage element are given in Appendix. The energy conversion efficiency of the PV panels is low, which necessitates the need of maximum power point tracking (MPPT) to extract maximum power under the existing environmental conditions [3]. Incremental Conductance (IC) method is an attractive MPPT technique based on instantaneous conductance of the PV array, which is computationally simple and easy to implement [18]. In this work, IC MPPT technique is employed to extract the maximum power from the PV array. Also V_{dc1}–V_{dc2}–V_{dc3}–V_{dc4} are regulated at 100V. The 5-level DCI, operated with multicarrier pulse width modulation technique, has the peak output voltage of 200V. The performance of proposed standalone microgrid architecture for operating modes II–IV, discussed in the following sub-sections, is tabulated in Table - III.

MODE-I

Fig. 4 (a) shows the steady state performance of the standalone microgrid with 5-level DCI based HGS operating under Mode-II. The load demand is 1249W and power available from PV1–PV2 and DG1–DG2 are 316W and 483W, respectively. This cannot meet the load demand and hence, B1–B2 are subjected to controlled discharging so as to and provide 450W to meet the load demand. The total harmonic distortion of load current (THD) is 4.33%.

MODE-II

Similarly, the steady state performance of the proposed standalone microgrid operating under Mode-III is shown in Fig. 4 (b). The load demand is 750W and power available from PV1–PV2 and DG1–DG2 are 804W and 288W, respectively. The power generation exceeds the load demand. This excess power can be utilized to charge the battery packs. Hence, in this mode B1–B2 are operate under controlled charging so as to and store excess 342W. This stored energy can be utilized when the generated power is lesser than the demand, as in case of Mode–II and IV. THD of the load current is 4.85%.

MODE-III

Fig. 4 (c) shows the steady state performance of the proposed standalone microgrid operating under Mode–IV. As this mode involves the periods of low light intensity and night time, the PV power is unavailable. When the load demand is 947W and power available from PV1–PV2 and DG1–DG2 are 0W and 369W, respectively. To meet the load demand, B1–B2 provide the stored energy during Mode – III to the load through the bidirectional dc-dc converter and DCI. The battery operates in discharging mode to supply 578W to meet the load demand. THD of the load current is 4.77%.

CONCLUSIONS

This study presents the results of a MATLAB/SIMULINK modelling effort into a stand-alone microgrid that employs a 5-level DCI based on HGS. Multiple configurations of the system are compared in terms of performance. The suggested standalone microgrid design includes 5-level DCI, which keeps the THD of the output current below 5%. Using an IC algorithm on the PV arrays guarantees the most power is drawn from the panels. Whether or not the PV power and DG can satisfy the load requirement determines whether or not the battery packs are in charging mode or discharging mode. The battery pack is charged in Mode-III, while it is discharged in Modes-II and IV. Integrating DGs into HGS improves the system's dependability and capacity to function independently. These benefits may be realised even in the absence of synchronisation or basic current extraction, both of which are often required for integrating DGs into conventional, grid-connected power systems. This is a bonus that helps make the proposed plan a more viable option for rural electrification with its other benefits, such as fewer components, improved system efficiency, and lower voltage stress on switches.

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