A five bus AC–DC hybrid nanogrid system for PV based modern buildings

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Abstract
A five bus AC–DC hybrid transformerless nanogrid system for modern buildings, and its associated control strategy that can operate all the buses simultaneously, is proposed in this paper. The nanogrid has five buses that can exchange power among themselves. This feature improves the reliability of power availability in the system. Two DC buses and one AC bus can be operated in standalone mode as well as in grid connected mode which enables the scheme to operate with available DC microgrids and the AC utility grid. The PV array and the battery bank are interfaced with the remaining two buses which are PV bus, and the battery bus, respectively. In order to reduce the number of serially connected battery units, the voltage rating of the battery bus is kept low. Similarly, the voltage rating of the PV bus is maintained at a medium level to decrease the number of serially connected modules. Hence the effect of shading is minimized. The control strategy of the system is developed to judiciously operate all the buses. In order to validate the viability of the system, exhaustive experimental studies are carried out utilising a laboratory scale 1.2 kW nanogrid system developed for the purpose.

1 INTRODUCTION

Modern buildings (MB) are anticipated to have a local generation of electric power in their premises to fulfil most of their electrical power demand [1, 2]. Further, the installed capacity of the renewable energy sources can be reduced if the loads which may either be AC or DC, for example, fan loads, lighting loads, refrigerating loads, heating loads etc. are dealt with in an efficient and optimal fashion [3]. In order to accomplish this, it is required to have both AC and DC buses with multiple voltage levels where the renewable energy sources (RES), the battery, and the various types of loads can be connected to an appropriate bus of the building [4]. Most of the modern loads, for example, LED, CFL based lighting loads, personal computers, LED/LCD television sets, mobile phone chargers etc. are DC in nature, and require low voltage DC supply for their operation [5]. Hence the aforesaid DC loads and the battery are generally interfaced with a 48 V DC bus. Further, the output of solar photovoltaic (PV) system which is commonly employed in residential applications, is also DC in nature. The PV bus is required to have a low voltage rating to minimise the number of serially connected units which minimises the effect of shading due to obstacles like trees, adjacent buildings etc. which is quite usual in case of rooftop PV installations [6]. However, for a moderate power level, the selection of low voltage PV array increases losses in the system. Hence, considering all the aforementioned issues if the PV array is connected to a medium voltage bus, its performance can be optimised. On the other hand, high power loads, for example, electric vehicle chargers, and modern inverter controlled variable speed compressor based DC refrigerators, DC air conditioning units and DC washing machines can be interfaced with either 380 V or 48 V DC bus depending on their voltage requirement [4, 5]. Instead of connecting to the conventional AC bus (230 V, 50 Hz, or 110 V, 60 Hz), if the DC loads and RES are interfaced with the DC buses of appropriate voltage levels, the number of conversion stages can be minimised [7, 8]. Hence the reliability, efficiency, and compactness of the overall system are significantly improved. This also leads to a considerable reduction in harmonic content of the AC grid current, $i_g$ [9]. However, there may be some single phase induction...
motor based ceiling fans, AC refrigerator, AC air conditioning unit, AC washing machine and pumping loads, heating loads, conventional fluorescent lamps etc. in MB which is required to be connected to the conventional AC grid [4]. In addition, MB may require the service of a local microgrid or nanogrid which supply power at 48 V and 380 V DC. Hence, the power system of an MB is an AC–DC hybrid low power nanogrid system consisting of multiple interfacing buses having different voltage levels [9, 10]. A block diagram depicting the aforementioned nanogrid system in a typical MB is shown in Figure 1. This type of nanogrid would serve as the power system network of a smart home [11] in the near future. In that case, along with the aforementioned features, the turn ON and turn OFF control of the buses, and the loads are required to be operated from a remote location [11].

An extensive review of various power topologies and control strategies of AC–DC hybrid microgrid and nanogrid is reported in [12]. The research gaps mentioned in [12] and the extensive survey carried out in this domain reveal the availability of a limited number of systems in the literature that can satisfy the requirement of nanogrids for low power MBs. Two different techniques to control battery storage and AC side grid are reported in [3, 13]. However, low AC and DC voltage levels are considered in case of [13], and storage is considered at the high voltage DC side in case of [3]. Further, in both cases, a single level for the DC voltage is considered. Therefore, due to the increase in AC–DC power conversion stages, and also due to an increase in the number of serially connected storage units, these control strategies cannot be optimally utilised in case of MBs. A control strategy that focuses on the interconnection of AC grid to the DC grid for residential DC distribution is reported in [14], however, no information regarding simultaneous control of storage and PV along with AC–DC hybrid grids is made available. The energy management and control strategies that are reported in [15–20], are also not directly suitable for the proposed application.

Single stage schemes that are meant for solar PV based residential applications are reported in [9, 10] and [21]. However, the schemes reported in [9] and [21] have not considered the standard DC voltage levels of 48 V and 380 V. Further, simultaneous control of AC grid, DC grid, PV, and battery is not possible in all the operating modes of the scheme reported in [9]. On the other hand, only one voltage level is considered in [10]. Further, the PV and battery are either directly interfaced to the high voltage DC grid through an interlinked converter [10] or is connected directly at the high voltage side of the converter [21]. Hence the numbers of serially connected PV and battery units in the schemes reported in [21] and [10] are high. In addition to this, the presence of a grid frequency transformer at the point of common coupling increases the volume, size, and weight of these schemes [22]. A transformerless scheme along with the control of AC–DC grid, PV, and storages comprising of battery and super capacitor is reported in [23]. However, the scheme is developed without taking into consideration the standard voltage levels for AC grid (ranging from 110 V to 240 V), and for the DC grid (48 V and 380 V). Further, only one voltage level is considered for this scheme. As a result, if the schemes reported in [9] and [23] are required to be upgraded to the standard DC voltage level of 380 V, the number of DC–AC/AC–DC conversion stages need to be increased considerably.

The research gaps that can be inferred from the above discussion are:

(i) None of the schemes that are available in the literature can accomplish the requirement of MB which needs to have multiple AC and DC types of buses having different voltage levels.
(ii) All the buses in an MB need to have the property to exchange power seamlessly between them.
(iii) The RES, and the storage element are to be operated optimally so that the power drawn from the utility grids, and the local microgrids or nanogrids remains to be minimal.
(iv) The overall control strategy needs to be simple enough such that it can be implemented on a low cost digital signal controller (DSC).

In order to address the aforementioned issues a five bus AC–DC hybrid nanogrid system for FBs and its related control strategy are proposed in this paper. The power circuit configuration of the proposed nanogrid is realised by employing conventional power electronic DC–DC and DC-AC converters reported in the literature. The various features of the proposed nanogrid are:

(i) The system has four DC voltage buses among which two buses are dedicated for interfacing PV, and battery storage, and two buses are meant to provide two different levels of voltages.
(ii) Out of these two buses one is configured for 48 V voltage level, and another one is configured for 380 V voltage level. The 48 V and 380 V buses are designed to source as well as to sink power.

(iii) In addition to the DC buses an AC bus has also been provided which can feed the local AC loads as well as it can exchange power with the utility grid.

(iv) The 48 V and 380 V DC buses, and the AC bus are designed to operate in the grid connected as well as in standalone mode.

(v) Due to the availability of several buses at different voltage levels, a given load can be interfaced with an appropriate bus, which leads to a reduction in the number of power conversion stages of any load having multiple of such stages. As a consequence of this, the overall efficiency of the load improves. This also results in reduction in component count, hence the cost of the interfacing unit of the load gets reduced.

(vi) The battery bus is designed with a low voltage rating to minimise the series connection of individual units.

(vii) The PV bus is designed to have a medium voltage rating to accrue the advantages which have already been mentioned earlier.

(viii) At any given instant all the five buses can exchange power seamlessly among themselves. Hence the reliability of power availability is improved significantly.

(ix) The turn ON and turn OFF control of the buses and the loads are controlled through DSC, as a result the user may have the facility to operate them remotely.

(x) A simple two stage control strategy based on the truth table and the conventional PI controller is considered to control the nanogrid.

(xi) The proposed scheme does not require the service of a line frequency transformer (LFT), hence the size, weight and volume are significantly less as compared to the schemes having LFT.

The realisation of the proposed nanogrid system is discussed in Section 2. The detailed control strategy of the system is presented in Section 3. A 1.2 kW laboratory scale nanogrid system has been fabricated. In order to confirm the effectiveness of the system, exhaustive experimental studies verifying all the major modes of operation have been carried out, and the results are presented in Section 4.

2. REALISATION OF THE PROPOSED NANOGRID SYSTEM

The schematic circuit diagram of the proposed AC–DC hybrid transformerless nanogrid system for MB is shown in Figure 2. The five buses of the system are denoted as $BU_{380}$, $BU_{48}$, $BU_{ac}$, $BU_{bat}$, wherein, $BU_{380}$ is the 380 V DC bus, $BU_{48}$ is the 48 V DC bus, $BU_{ac}$ is the AC voltage bus, $BU_{bat}$ is the bus where PV is connected, and $BU_{bat}$ is the bus where battery is connected.

The standalone loads that are connected to $BU_{380}$ are $R_{1380}$ and $R_{2380}$, while the loads $R_{148}$ and $R_{248}$ are connected to $BU_{48}$. The voltage level, $v_{ac, L}$ of $BU_{ac}$ can be selected to be in the range of 110 V to 240 V along with the required frequency as are applicable in the country of operation of the MB. In this paper the utility grid voltage, $v_{g}$ and its operating frequency are chosen to be 230 V and 50 Hz, respectively. The loads connected to $BU_{ac}$ are $R_{1ac}$ and $R_{2ac}$. A bidirectional DC–DC converter comprising of capacitors, $C_{48}$, $C_{1}$, inductor, $L_{1}$, switches, $S_{1}$, $S_{2}$ is employed to exchange power between $BU_{48}$ and $BU_{ac}$. Similarly another bidirectional DC–DC converter consisting of capacitors, $C_{bat}$, $C_{48}$, inductor, $L_{bat}$, switches, $S_{b1}$, $S_{b2}$ is employed to exchange power between $BU_{bat}$ and $BU_{48}$.

In order to obtain high DC voltage gain either transformer based DC–DC schemes reported in [24, 25] or transformerless DC–DC scheme reported in [26] are considered in the literature. However, all of these schemes have the following disadvantages: (i) higher number of active and passive component counts, (ii) increased control complexity, (iii) unidirectional power flow can only be realised. Therefore, these schemes can not be employed for application involving MB. On the other hand the buck-boost based high gain DC–DC stage which is reported in [27] is bidirectional in nature, and complexity of operation is also less. Further, component count of this scheme is also less as compared to the other schemes. Hence the high gain DC–DC stage
reported in [27] is employed to exchange power between $BU_{380}$ and $BU_{pv}$. This stage is realised by having inductor, $L_2$, capacitor, $C_1$, $C_2$, and switches $S_3$, $S_4$. For continuous mode of conduction (CCM) the relation between, PV array voltage, $V_{pv}$ and the output of the high gain DC–DC stage, $V_{hvo}$ is as follows,

$$V_{hvo} = \frac{d_3}{1 - d_3} V_{pv}$$  \hspace{1cm} (1)$$

wherein, $d_3$ is the duty ratio of $S_3$. The sum of the voltages $V_{pv}$ and $V_{hvo}$ which is $V_{380}$ can be expressed as

$$V_{380} = V_{pv} + V_{hvo} = \frac{d_3}{1 - d_3} V_{pv} + V_{pv}$$

$$V_{380} = \frac{1}{1 - d_3} V_{pv}.$$  \hspace{1cm} (2)$$

Therefore, higher overall voltage gain is achieved from this stage as compared to the conventional buck-boost stage as $
\frac{V_{380} + V_{380}}{V_{pv}} > \frac{V_{380} + V_{380}}{V_{pv}}$. The bus $BU_{380}$ is interfaced to $BU_{ac}$ through a H-bridge inverter consisting of switches, $S_5$-$S_8$, and filter elements, $L_{g1}$, $L_{g2}$ and $C_g$.

3 | CONTROL OF THE PROPOSED NANOGRID SYSTEM

In order to control the proposed nanogrid system a simple two stage control strategy based on truth table and the conventional PI controller is proposed. The main features of this control strategy are (i) all the five buses are controlled simultaneously, (ii) the buses can exchange power seamlessly among themselves, (iii) PV can be operated at maximum power point (MPP) or non-MPP whenever required, (iv) over-charging and discharging of the battery pack is prevented, hence increasing its life, and (v) power from/to the AC grid is absorbed/injected at unity power factor. The two stages of this control strategy are mentioned as follows:

3.1 Stage 1: Determination of modes of operation

In a practical installation the signals indicating the presence or absence of AC or DC grids are generated by 'islanding detection' algorithms [28, 29]. However, islanding detection is not considered in the scope of the work presented in this paper. Hence to realise the presence or absence of any source across the five buses, five breakers, $B_{380}$ for 380 V DC grid, $B_{48}$ for 48 V DC grid, $B_{pv}$ for PV, $B_{bat}$ for battery and $B_{ac}$ for 230 V AC grid are employed. In order to turn ON or OFF any bus whenever required, provisions are made to control these switches through DSC. The decision regarding the mode in which the system is required to be operated, and also the MPP and non-MPP operation of the PV are decided by switching states of the five breakers. This decision making process is shown in the form of a truth table in Table 1, wherein the ON state of any breaker is denoted by 1, while 0 represents its OFF state. The output of the truth table provides information regarding the particular mode out of the 17 modes in which the system is required to operate. Further, the information regarding the MPP or non-MPP operation of the PV is provided by the state of the flag, 'mpp', wherein 1 is assigned to denote MPP operation while 0 denotes non-MPP operation. Mode 3 is divided into two sub modes, mode 3M and mode 3N. Mode 3M represents the operation of PV at MPP in mode 3 while the operation of PV at non-MPP in the same mode is denoted by 3N. In mode 3 while battery and PV are present, depending on (i) the overall load demand, (ii) the maximum power absorption or delivering capability of the battery, and (iii) power available from the PV, the control of PV would

| $B_{380}$ | $B_{48}$ | $B_{ac}$ | $B_{pv}$ | $B_{bat}$ | Mode | mpp |
|----------|---------|---------|---------|----------|------|-----|
| 0        | 0       | 0       | 0       | 0        | 0    | 0   |
| 0        | 0       | 0       | 1       | 1        | 1    | 0   |
| 0        | 0       | 1       | 0       | 2        | 2    | 0   |
| 0        | 0       | 1       | 0       | 1        | 3M/3N| 1/0 |
| 0        | 0       | 1       | 1       | 0        | 4    | 0   |
| 0        | 1       | 0       | 0       | 0        | 6    | 0   |
| 0        | 1       | 0       | 1       | 6        | 6    | 0   |
| 0        | 1       | 1       | 0       | 7        | 7    | 1   |
| 0        | 1       | 1       | 1       | 7        | 7    | 1   |
| 0        | 1       | 1       | 0       | 8        | 8    | 0   |
| 0        | 1       | 1       | 1       | 9        | 9    | 1   |
| 1        | 0       | 0       | 0       | 0        | 10   | 0   |
| 1        | 0       | 0       | 0       | 1        | 10   | 0   |
| 1        | 0       | 1       | 0       | 11       | 11   | 1   |
| 1        | 0       | 1       | 1       | 12       | 12   | 0   |
| 1        | 0       | 1       | 1       | 13       | 13   | 1   |
| 1        | 1       | 0       | 0       | 0        | 14   | 0   |
| 1        | 1       | 0       | 0       | 1        | 14   | 0   |
| 1        | 1       | 0       | 1       | 0        | 15   | 1   |
| 1        | 1       | 0       | 1       | 1        | 15   | 1   |
| 1        | 1       | 0       | 0       | 0        | 16   | 0   |
| 1        | 1       | 1       | 0       | 17       | 17   | 1   |
| 1        | 1       | 1       | 1       | 17       | 17   | 1   |
be shifted from MPP to non-MPP or vice versa. The selection of 3M or 3N is decided as per the flow chart shown in Figure 3, wherein shifting of mode is decided by the prevailing magnitude of \( V_{48} \) and the current value of the flag, ‘mpp’. It may also be noted that PV is always operated at MPP, if any of the grids is present, and at the same time the battery converter continuously charges the battery until its maximum capacity is reached. Also, current limits are set in the control loop to prevent overcharging and over-discharging of the battery, hence enhancing its life. If the load demand is more than the set current limit of the battery, \( V_{48} \) falls, and as shown in Figure 3 when it hits the set limit of 35 V the system is shut down. When the battery converter charges the battery with its set current limit in 3M, if the total load power becomes less than the available PV power, \( V_{48} \) increases, and as shown in Figure 3 the mode of operation gets shifted from 3M to 3N as \( V_{48} \) hits its set limit 55 V. On the other hand while the battery converter charges the battery in 3M, if the total load power is greater than total PV power, \( V_{48} \) falls. Subsequently, as shown in Figure 3 the battery converter changes its operation from ‘charging only’ to ‘48 V control’ when \( V_{48} \) lies in the range of 35–40 V till the maximum discharge current limit of the battery is reached.

### 3.2 Stage 2: Control of inverter/converters associated between the two buses

Once the mode of operation of the interface is obtained from Stage 1, the control objectives of each converter or inverter of the nanogrid system are decided by setting or resetting of various flags as mentioned in Tables 2–5. The control of each converter is elaborated as follows:

#### 3.2.1 Control of inverter

As shown in Table 2 the operation of the H-bridge inverter has three control objectives, (i) voltage control of 380 V DC bus (\( V_{380} \) control), (ii) operation as a standalone inverter (SAI control), (iii) OFF state of the inverter, and these objectives are identified by the state of three flags. The flag, \( IN_{380} \) represents voltage control of 380 V DC bus, the flag, \( IN_{sa} \) represents the standalone operation of the inverter, and the flag, \( IN_{on} \) represents the ON/OFF state of the inverter. The status (either set to 1 or reset to 0) of these three flags determine the controlling state of the inverter. Once the state of the flags are known, the switching pulses for the switches, \( S_5–S_8 \) are generated from the control block diagram as shown in Figure 4. It may be noted that the bipolar pulse width modulation technique is adopted to generate the switching pulses of the inverter. In \( V_{380} \) control the

| Table 2 | Control of inverter |
|---------|--------------------|
| \( V_{380} \) Control | SAI Control | OFF State |
| 4, 5   | 1, 2, 3M, 3N, 6, 7, 10, 11, 14, 15 | 0, 8, 9, 12, 13, 16, 17 |
| \( IN_{380} \) = 1, \( IN_{sa} \) = 0, \( IN_{on} \) = 1, \( IN_{380} \) = 0, \( IN_{sa} \) = 0 | \( IN_{380} \) = 1, \( IN_{sa} \) = 1, \( IN_{on} \) = 0 |

#### 3.2.2 Control of converter associated between \( BU_{380} \) and \( BU_{48} \)

| Table 3 | Control of converter associated between \( BU_{380} \) and \( BU_{48} \) |
|---------|--------------------|
| 380 V Control | 260 V Control | MPP Control |
| 2, 3N  | 1, 4, 6, 8, 10, 12, 13, 14, 16 | 3M, 5, 7, 9, 11, 13, 15, 17 |
| \( S34_{380} \) = 1 | \( S34_{380} \) = 0 | \( S34_{380} \) = 0 |
| \( S34_{260} \) = 0 | \( S34_{260} \) = 1 | \( S34_{260} \) = 0 |
| \( S34_{mp} \) = 0 | \( S34_{mp} \) = 0 | \( S34_{mp} \) = 1 |

| Table 4 | Control of converter associated between \( BU_{48} \) and \( BU_{bat} \) |
|---------|--------------------|
| 48 V Control | 120 V Control | 380 V Control |
| 2, 3N, 4, 5, 10, 11, 12, 13, 14, 15, 16, 17 | 1, 6, 8 | 3M, 7, 9 |
| \( S12_{48} \) = 1 | \( S12_{48} \) = 0 | \( S12_{48} \) = 0 |
| \( S12_{120} \) = 0 | \( S12_{120} \) = 1 | \( S12_{120} \) = 0 |
| \( S12_{380} \) = 0 | \( S12_{380} \) = 0 | \( S12_{380} \) = 1 |

#### 3.2.3 Control of converter associated between \( BU_{48} \) and \( BU_{bat} \)

| Table 5 | Control of converter associated between \( BU_{48} \) and \( BU_{bat} \) |
|---------|--------------------|
| Charging Only | 48 V Control |
| 2, 3N, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17 | 1, 3M |
| \( SB_{co} \) = 1, \( SB_{48} \) = 0 | \( SB_{co} \) = 0, \( SB_{48} \) = 1 |

#### FIGURE 3 Mode selection flow chart for mode 3M and mode 3N

#### FIGURE 4 Control block diagram of inverter
current, \( i_{ac} \) flowing through \( L_{ac} \) is controlled to be in-phase with the \( v_{ps} \), wherein the amplitude of the reference of \( i_{ac} \) is generated from DC bus voltage controller. In SAI control, the inverter controls \( v_{ad} \), to maintain a 230 V, 50 Hz AC voltage at \( BU_{ac} \). The unity sine template, \( \chi_s \), is generated from a phase locked loop (PLL) during \( V_{380} \) control operation, whereas a unity sine template of 50 Hz frequency, \( \chi_{ho} \), is generated from a harmonic oscillator during SAI control operation.

3.2.2 | Control of converter associated between \( BU_{380} \) and \( BU_{pv} \)

As shown in Table 3 the operation of the converter associated with \( BU_{380} \) and \( BU_{pv} \) has three control objectives, (i) maintaining the \( BU_{380} \) voltage at 380 V or non-MPP control of PV (380 V control), (ii) controlling \( V_{380} \) at 260 V (260 V control), (iii) MPP control of PV (MPP control), and these objectives are identified by the state of three flags. The flag, \( S34_{380} \) represent 380 V control, the flag, \( S34_{260} \) represents 260 V control, and \( S34_{mpp} \) represents MPP control of the PV. The status (either set to 1 or reset to 0) of these three flags determine the controlling state of this converter. Once the state of the flags are known, the switching pulses for the switches, \( S_1, S_2, S_3 \) are generated from the control block diagram as shown in Figure 5. In 380 V control operation, the converter maintains \( V_{380} \) at a voltage level of 380 V.

3.2.3 | Control of converter associated between \( BU_{pv} \) and \( BU_{48} \)

As shown in Table 4, the operation of the converter associated with \( BU_{pv} \) and \( BU_{48} \) has three control objectives, (i) controlling \( V_{48} \) at 48 V (48 V control), (ii) controlling \( V_{ps} \) at 120 V (120 V control), (iii) maintaining the \( BU_{380} \) voltage at 380 V (380 V control), and these objectives are identified by the state of three flags. The flag, \( S12_{48} \) represents 48 V control, the flag, \( S12_{120} \) represents 120 V control, and the flag, \( S12_{380} \) represents 380 V control of the converter. The status (either set to 1 or reset to 0) of these three flags determine the controlling state of this converter. Once the state of the flags are known, the switching pulses for the switches, \( S_1, S_2 \) are generated from the control block diagram as shown in Figure 6. In 48 V control operation the converter maintains 48 V at \( V_{48} \), whereas \( V_{ps} \) is maintained at 120 V during 120 V control operation. In 380 V control operation the converter controls \( V_{380} \) at a voltage level of 380 V.

3.2.4 | Control of converter associated between \( BU_{48} \) and \( BU_{bat} \)

As shown in Table 5, the operation of the converter associated with \( BU_{48} \) and \( BU_{bat} \) has two control objectives, (i) charge the battery at a fixed voltage (charging only), (ii) maintaining \( V_{48} \) at 48 V (48 V control), and these objectives are identified by the state of two flags. The flag, \( SB_{48} \) represents charging only operation of the battery, and the flag, \( SB_{48} \) represents 48 V control operation of the converter. The status (either set to 1 or reset to 0) of these two flags determine the controlling state of this converter. Once the state of the flags are known, the switching pulses for the switches, \( S_{b1}, S_{b2} \) are generated from the control block diagram as shown in Figure 7. In charging only mode the converter charges the battery either with its maximum allowable charging current or by maintaining a fixed voltage across it until its state of charge reaches at 100%. In 48 V control operation, the converter maintains \( V_{48} \) at 48 V depending on the charging and discharging current limit set for the battery controller.

4 | EXPERIMENTAL VERIFICATION

The viability of the proposed nanogrid system and its control strategy are validated through a detailed simulation study on Matlab/Simulink platform. In addition to this, the same is also verified with an exhaustive experimental study on a laboratory scale 1.2 kW nanogrid system. However, only experimental per-
formance of this system is presented in this section for the sake of brevity. The photograph of the experimental setup along with the loads and sources that are used to emulate PV, DC and AC grids are shown in Figure 8. The components/parameters that are used to realise the experimental setup, are provided in Table 6. The settings of voltage and current of the DC and AC power supplies which are used to emulate 380 V DC grid, 48 V DC grid, 230 V AC grid and PV array are provided in Table 7, wherein $V_{ac}$, $I_{ac}$ and $I_{mpp}$ are open circuit voltage, short circuit current and MPP current of the PV array, respectively. The voltage rating of the battery bus is considered to be 36 V, and a battery pack of required voltage level is realised by three serially connected 12 V ‘AmaraRaja’ make ‘Quanta-12AL065’ batteries. The charging and discharging current limits of the battery are set to 7.5 A and 12 A, respectively. Hence the battery pack acts as a load of 270 W while it receives power with its set charging current limit. The battery current is denoted by $i_{bat}$, while its charging and discharging currents are denoted by $+i_{bat}$ and $-i_{bat}$, respectively. The settings of six rheostats which are considered as local loads connected to the 48 V DC grid, 380 V DC grid, and AC grid are provided in Table 8. The gain of all the controllers associated with the control loops of inverter and converters are computed through small signal modelling presented in [30]. The gains of all the controllers are provided in Table 9. The working of the proposed nanogrid is shown in Sections 4.1 to 4.6 wherein all the major operating modes are considered. Subsequently, an overall inference that can be drawn from the experimental results is presented in Section 4.8. In order to show the ability of the proposed nanogrid to operate satisfactorily in different operating modes, various sequence of events which are generated through DSC, are applied to the interface. The aforesaid events are denoted as follows: Turning ON instants of $E_{a1}, E_{a2}, R_{148}, R_{248}, R_{1380}, R_{2380}, R_{a1}$ and $R_{a2}$ are represented by $E_{a1N}, E_{a2N}, E_{31N}, E_{32N}, E_{a1N}$ and $E_{a2N}$, respectively, whereas their turning OFF instants are represented by $E_{a1F}, E_{a2F}, E_{31F}, E_{32F}, E_{a1F}$ and $E_{a2F}$, respectively. Similarly turning ON instants of $B_{p}$ and $B_{a}$ are represented by $E_{pON}$ and $E_{bON}$, whereas their turning OFF instants are represented by $E_{pOF}$ and $E_{bOF}$.

### 4.1 Operation in mode 1

The operation of the proposed system in this operating mode is demonstrated by keeping $B_{a8}, B_{380}, B_{a7}, B_{p}$ OFF. The working of the scheme with DC loads is shown in Figure 9(a), while Figure 9(b) depicts the event when battery is supplying $R_{a1}$. As the discharge current limit of the battery is set as 12 A, it is allowed to supply a maximum power of 432 W. The operating

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**TABLE 6** Components/parameters and their values used to realise the system

| Components          | Value                  |
|---------------------|------------------------|
| $I_{f}, I_{s}, I_{bat}$ | 0.55 mH, 0.55 mH, 0.4 mH |
| $L_{f1}, L_{f2}, L_{bat}$ | 5 mH, 5 mH            |
| $C_{f1}, C_{f2}$ | 5 μF, 2 μF             |
| $C_{L1}, C_{L2}$ | 1100 μF, 1100 μF        |
| $S_{f1}, S_{f2}, S_{L1}, S_{L2}$ | C3M0065090D |
| Switching frequency, $f_{s}$ | 50 kHz                |
| MPPT algorithm      | Incremental conductance |
| Digital signal controller | TMS320F28335        |

**TABLE 7** Sources and their settings for the experimental study

| Source          | Equipment Used | Settings                  |
|-----------------|----------------|---------------------------|
| 380 V DC grid   | EPS9750-20     | 380 V, 5 A                |
| 48 V DC grid    | DSP50-60HD     | 48 V, 25 A                |
| 230 V AC grid   | 1 phase variac | 230 V, 10 A, 50 Hz        |
| PV emulator     | EPS9360-15     | $V_{ac} = 150 V, V_{mpp} = 120 V, I_{ac} = 4.4 A, I_{mpp} = 4 A$ |
| Battery pack    | 12 V, 65 Ah battery | Nominal pack               |

**TABLE 8** Loads and their ratings for the experimental study

| Load               | Rating/Unit | Quantity |
|--------------------|-------------|----------|
| 380 V DC load      | 963 Ω, 175 W, 0.46 A | 2        |
| 48 V DC load       | 30 Ω, 75 W, 1.56 A   | 2        |
| 230 V AC load      | 300 Ω, 175 W, 0.77 A | 2        |

**TABLE 9** Gain of the PI controllers

| PI Controllers Associated With | Gains              |
|--------------------------------|--------------------|
| Inverter                       | $K_{p1} = 0.02, K_{i1} = 0.05,$ |
|                                | $K_{p2} = 0.6, K_{i2} = 0.006,$ |
|                                | $K_{p3} = 10$      |
| Converter between $BU_{380}$ and $BU_{ja}$ | $K_{p4} = 0.3, K_{i4} = 0.1,$ |
|                                | $K_{p5} = 0.001, K_{i5} = 0.001$ |
| Converter between $BU_{ja}$ and $BU_{48}$ | $K_{p6} = 0.001, K_{i6} = 0.01$ |
| Converter between $BU_{48}$ and $BU_{bat}$ | $K_{p7} = 0.5, K_{i7} = 0.1,$ |
|                                | $K_{p8} = 0.1, K_{i8} = 1.5$ |

$a =$ during output current control, $b =$ during output voltage control.
4.2 | Operation in mode 2 and mode 3M

In mode 2 only PV supplies power, and is operated in non-MPP while in mode 3M, both the battery and PV are present, and PV is operated in MPP. The operation of the scheme in these two modes are shown in Figure 10, wherein \( P_{pp} \) is the power extracted from the PV array. In order to show both the aforementioned operations along with the switching of operating modes, initially the operation in mode 3M is initiated while the insolation level of the PV is maintained at 10%, and the battery is made to supply a load of 250 W. In this condition PV is operated in MPP as maximum power of PV is 48 W which is less than the total load demand, therefore the battery supplies the difference of the power. While the insolation of PV is gradually increased from 10% to 80% the control algorithm tracks the MPP effectively, and PV power injection increases from 48 W to 384 W. When \( P_{pe} \) exceeds the total load demand, the control strategy shifts the operation of the battery from discharging to charging, thereby storing the surplus power in the battery. In order to show the transfer in operation from mode 3M to mode 2, \( B_{bat} \) is turned OFF. The controller shifts to the required mode of operation, and the system is operated in non-MPP as the total load demand is less than the available MPP power of PV.

4.3 | Operation in mode 4

The operation of the system in this mode is shown in Figure 11, and it is realised by keeping \( B_{380}, B_{48}, B_{pe} \) OFF. The current injected to the AC grid is represented by \( i_{ac} \). The operation of the scheme while it is supplying \( R_{148}, R_{1380} \) and charging the battery is shown in the same figure. Subsequently a sequence of events as shown in Figure 11 are applied to the interface to demonstrate its successful operation in this mode.

4.4 | Operation in mode 6

In this case, \( B_{380}, B_{48}, B_{pe} \) are kept OFF. The operating sequence of various loads and battery is shown in Figure 12, wherein \( i_{48S} \) is the current supplied by the 48 V DC grid. The operation of the scheme with DC loads is shown in Figure 12(a), while Figure 12(b) depicts the operation with AC loads. It may be noted that in Figure 12(b) the sequence of events is shown by considering \( R_{148}, R_{248}, R_{1380}, \) battery and \( R_{ac1} \) into operation.
4.5 | Operation in mode 7

In this mode PV and battery are operated with 48 V DC grid. PV is switched ON at 10% insolation while \( R_{148}, R_{1380} \) and battery are already in operation, and \( i_{bat} \) has attained its steady state. In addition to this as shown in Figure 13(a), \( R_{248} \) and \( R_{2380} \) are turned ON to increase the total power output of the 48 V DC grid. Subsequently the insolation of the PV is gradually varied from 10% to 100%. As shown in Figure 13(b), the control algorithm operates the PV array at MPP, and extract maximum power from it during the entire insolation variation range. It may be noted from Figure 13(a) that the power supplied by the 48 V DC grid decreases while power injection from the PV increases.

4.6 | Operation in mode 10

The operation of the nanogrid in this operating mode is shown in Figure 14 while \( B_{48}, B_{380}, \) and \( B_{ac} \) are kept OFF. The operating sequence of various events with DC loads is shown in Figure 14(a), while Figure 14(b) depicts the operation with \( R_{ac1} \) and \( R_{ac2} \). The current supplied by the 380 V DC grid is denoted by \( i_{3803} \).

4.7 | Switching of 48 V DC grid, 380 V DC grid, and AC grid

The switchings of 48 V DC grid, 380 V DC grid, and 230 V AC grid have been shown in Figure 15, with a total load of 250 W. Initially \( B_{48} \) has been kept ON, while \( B_{380}, \) and \( B_{ac} \) are kept OFF. Turning ON instants of 48 V DC grid, 380 V DC grid and AC grid are represented by \( E_{48N}, E_{380N}, \) and \( E_{agN} \), respectively, whereas their turning OFF instants are represented by \( E_{48F}, E_{380F}, \) and \( E_{agF} \), respectively. It can be inferred from Figure 15 that the proposed scheme can transfer the operation from one grid to the another without tripping the loads.

4.8 | Overall inference from the experimental results

It can be verified from Figures 9–12, and Figure 14 that the proposed nanogrid system can maintain desired voltage levels across all the buses, and can exchange power among themselves. Hence the local loads that are connected to the buses get uninterrupted power in spite of the presence or absence of the grid at those buses. Hence the reliability of power availability in the buses improves significantly. Also as shown in Figure 10, the proposed system is able to operate the PV array at MPP, and as well as in non-MPP depending on the power requirement of the load, and the state of charge (SOC) of the battery. Further, while the controller changes the operation of PV from MPP to non-MPP, \( V_{pe} \) and \( V_{hvo} \) are adjusted appropriately so that \( V_{380} \) is always maintained at 380 V. It may be noted that when the battery is switched to \( BU_{bat} \), and it starts receiving power, \( i_{bat} \) reaches to its set limit depending on the difference existing between the reference voltage and \( v_{bat} \) at that instant. As shown in Figure 12, \( i_{bat} \) reaches to 7.5 A which is the set charging current limit of the battery. Hence the set current limits restrict over-charging and over-discharging of the battery thereby increasing its life.

A comparison of various nanogrid systems is presented in Table 10. It can be inferred from the various parameters as mentioned in the table that the proposed nanogrid system is a suitable candidate for MB application.
TABLE 10  Comparison of various systems

| Systems                      | $N_v$ | $V_{ph}$ | $V_b$ | CD | CM | T/F | $S_{suit}$ |
|------------------------------|-------|----------|-------|----|----|-----|------------|
| [7]                          | 1     | Low      | Low   | No | No | Yes | Low       |
| [9]                          | 1     | Low      | Low   | No | No | Yes | Low       |
| [10]                         | 2     | N/A      | N/A   | No | Yes| Yes | Medium    |
| [13]                         | 2     | Low      | Low   | No | No | Yes | Low       |
| [18]                         | 2     | N/A      | N/A   | No | No | N/A | Low       |
| [21]                         | 2     | High     | High  | No | No | Yes | Low       |
| [23]                         | 2     | N/S      | N/S   | No | No | No  | Low       |
| [31]                         | 2     | High     | Low   | No | Yes| Yes | Medium    |
| [32]                         | 2     | N/A      | N/A   | No | No | Yes | Low       |
| [33]                         | 2     | N/A      | N/A   | No | N/A| Low | Low       |
| Proposed                     | 3     | Medium   | Low   | Yes| Yes| No  | High      |

$N_v$ = Number of controlled buses where load can be connected, $V_{ph}$ = Voltage rating of PV bus, $V_b$ = Voltage rating of battery bus, CD = Control of buses and loads through DCC, N/S = Non standard voltage levels, CM = Compatibility with 48 V and 380 V local nanogrid and microgrid, T/F = Have line frequency transformer, $S_{suit}$ = Suitability of the system for MB.

5 | CONCLUSION

A five bus AC–DC hybrid transformerless nanogrid system for solar photovoltaic based modern buildings with integrated storage was proposed in this paper. The associated control strategy to operate all the buses simultaneously was also developed. The attractive features of this scheme and its control strategy were the following: (i) the buses which were connected to the AC and DC grid could be operated in grid connected or standalone mode, (ii) all the buses could exchange power among themselves, hence the reliability of power availability was improved significantly, (iii) the PV array could be operated at MPP or non-MPP depending on the load demand, SOC of the battery, and the availability of any grid, (iv) low and medium voltage rating of the battery bus and PV bus reduced the number of serially connected battery units, and PV modules. Hence the drop in power being evacuated from the PV due to the effect of shading was minimised. The transformerless configuration of the interface reduced the size, volume, and weight of the overall system. The various operating modes of the proposed scheme were demonstrated by performing detailed experimental studies on a laboratory scale 1.2 kW nanogrid system.

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How to cite this article: Dutta S, Chatterjee K. A five bus AC–DC hybrid nanogrid system for PV based modern buildings. IET Renew Power Gener. 2021;15:758–768. https://doi.org/10.1049/rpg2.12065