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Implementation of Multi-Level Bidirectional Inter Allied Converter Community for Global Power Sharing in Hybrid AC/DC Microgrids

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Abstract:
Bidirectional Inter-Allied Converters (BIACs) plays a major role in hybrid ac-dc microgrids (HM) forming as a bridging unit for power exchange between ac and dc subgrids. Overcoming the stress faced by single BIAC multiple converter structure i.e BIAC community came into existence. Considering advantages over two-level converters, multi-level converters sustain its position in today and future applications. Implementing the multi-level converter topology for distributed power management enhances the system efficiency with less amount of harmonic content. This paper presents implementation of Multi Level Bidirectional Inter Allied Converter (MLBIAC) community along with the Localized Distributed Proportional Integral Controller (LDPIC) located at each converter in HM for distributed power management. The localized distribution controller includes PI controller for system stability and which allows exchanging the information in more flexible way. To achieve the global power sharing by implementing MLBIAC in HM, the concepts like balanced power sharing, leading role transition, bidirectional power flow, system stability were analyzed and simulated using MATLAB/Simulink software.

Keywords: Global Power Sharing, Hybrid ac-dc microgrid, Localized distributed controller, System stability, Three-level Bidirectional Inter-Allied Converter.

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Introduction

Power supply to rural areas has always been a major challenge due to distance from power generation plant and it is highly capital intensive to build and maintain long distance transmission lines. Now-a-days generation of power through renewables has gained attention with reduction of fossil fuels. Hence, most of the research moved towards microgrids with medium voltage generation using renewables. With increase in load demand, penetrations of multiple sources for power generation, HM with medium voltage were developed [1]-[3]. In recent years, requirement of high power apparatus has begun in large number of industrial applications. Some of the motor drives and utility applications with medium voltage require megawatt power level. In case of medium voltage microgrids, majority of the problem arises in connecting only one power semi conductor switch directly. As a result, a Multi Level Power Converter (MLPC) has been introduced as an alternative in high power and medium voltage applications. The first MLPC with different voltage balance techniques such as diode clamping, flying capacitance and cascaded inverters between different levels including their applications were presented in [4]. Referring to previous work done by researchers, multilevel converters found its applications most in motor drive systems. But, coming across the work done in the area of renewables is much less and now it has greater deployment in the present scenario. Literature survey depicts the research work done on multilevel converters in the area of renewables.

The primary job of BIAC is to control the transfer of power between both the grids to meet supply and load demand. Various control and power management have been reported in the literature since last decade and various converter topologies and configurations of inter allied converter are reviewed in [5], [6]. Selection of BIAC depends on control objectives, which are to be fulfilled by it. In [7], a BIAC with pulse width modulation for conventional HM is presented to control ac and dc bus voltages when operated in voltage controlled mode and to balance power flow when operated in current controlled mode. Further, these converters are paralleled for large power interactions [8]. In [9], a quasi-z-source inverter with bidirectional property is implemented to reduce stress in switches. But, it has affected with stability problems. For better improvement of stability with reactive components less in number a switched boost bidirectional converter is presented in [10]. A modular interlinking converter is proposed in [11] with a battery storage at each of the module to increase the efficiency of the system. But from the economic point of view, use of large number of batteries increases the cost of the system.

In [12], inter allied converter with energy storage is implemented for autonomous operation of HM. Similar converter configurations are also implemented in [13] and [14]. Inter allied converters interfaced with either AC bus or DC bus is also presented in [15], [16]. But coming to power management issues to acquire global power sharing a huge number of droop control methods such as master slave current sharing control method [17], distributed coordination control method [18], distributed adaptive droop control method [19] and unified control method [20] were presented.

In HM, a two level BIAC with localized distributed controller is presented in [21] with distorted output voltages and switching losses, which indirectly affects the system stability and efficiency. Overcoming the aforementioned problems, a MLBIAC community i.e Three Level BIAC (TLBIAC) is implemented in HM to avoid overstress and to attain global power sharing by considering the concepts of balanced power sharing among the converter community based on their ratings, performing the role of first BIAC during its malfunction and attaining steady state stability in less time. The complete paper is organized as, section I presents introduction, section II presents configuration of TLBIAC, section III presents analysis of power management in HM, section IV represents results and section V is of conclusions.

Proposed multilevel topology for BIAC

A three level power converter with neutral clamped topology is considered as TLBIAC as bridging unit for power management in HM and is depicted in fig.1. The TLBIAC is structured with two capacitors C1 and C2 allied in series with a centre tap as neutral. The three phase power circuit consist of two pairs of switching devices in each phase. With the use of clamping diodes, the centre of each pair of devices is clamped to neutral. Increasing the levels from two to multi the power converter produces a staircase wave approaches to sine wave with minimal harmonic distortion. The operation of all the three phase legs is same.

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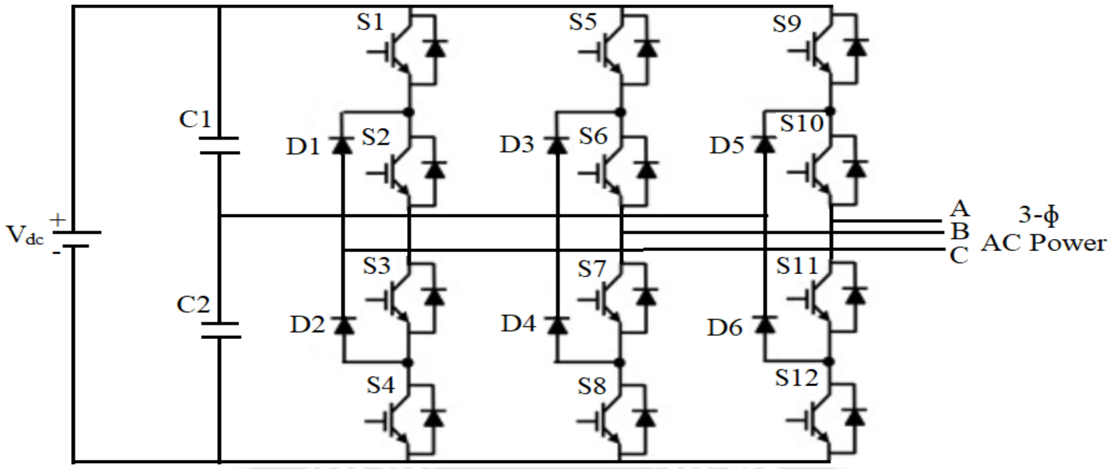

Fig.1. Power circuit of TLBIAC with diode clamped topology

Hence, for the operation of power converter, only one phase leg is considered. The switches S1 and S4 in phase leg 'A' work as main switching devices where as S2 and S4 functions as auxiliary devices, which helps to clamp the output voltage to the neutral point using clamping diodes D1 and D2. A carrier based three level pulse width modulation is implemented to drive the TLBIAC with the carrier frequency of 10 KHz in unsynchronized mode of operation. The TLBIAC with aforementioned configuration is implemented in HM for power management. As more number of renewable generation sources integrated into the HM to meet the load demand, large amount of power flows through the TLBIAC causing stress in it. To overcome the problem of using single TLBIAC, a community with 'x' number of TLBIACs were considered. A schematic of HM with TLBIAC community including the renewables, loads, and diesel generators as back up is shown in fig.2

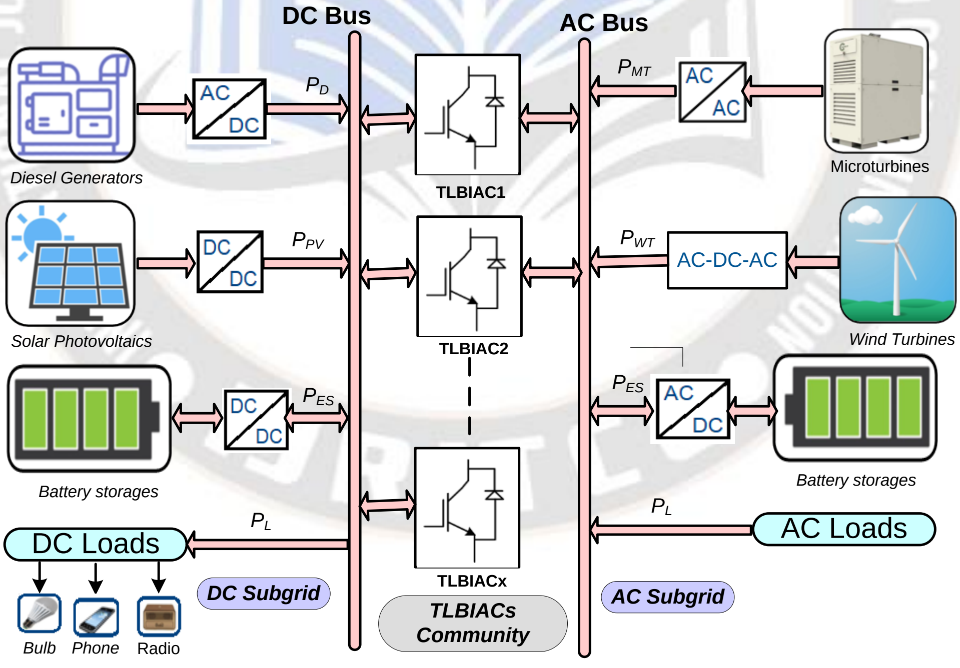

Fig.2. Layout HM with TLBIACs Community

Analysis of power flow using TLBIAC community in HM

Before analyzing the power flow in HM, energy sources except renewables are considered as dispatching units and its operation is under droop control is presented in fig.3.

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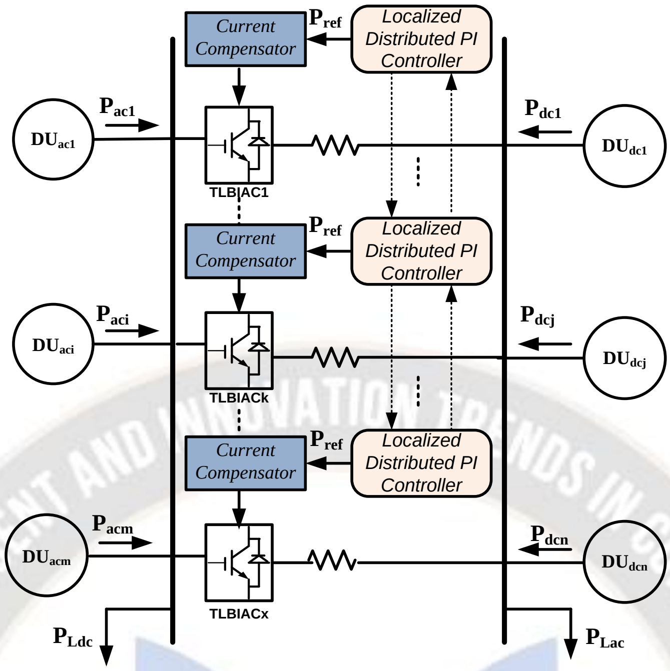

Fig.3 Proposed TLBIACs with control action

Extracting the information from classical power systems, to regulate the AC bus voltage (V_{ac}) and frequency (f_{ac}) i.e real power (P_{ac}) and reactive power (Q_{ac}) droop controllers are implemented. The droop equations are

$$f_{ac} = f_{ac\max} - a_{Pi} P_{aci}, \qquad i \in [1, m] \qquad (1)$$

$$V_{ac} = V_{ac\max} - a_{Qi} Q_{aci}, \qquad i \in [1, m] \qquad (2)$$

Where $V_{ac\max}$, $f_{ac\max}$ are allowable maximum values voltage and frequency and 'm' denotes total number of dispatching units of AC sub grid. a_P and a_Q denotes droop coefficients. $a_{Pi} = (f_{ac\max} - f_{ac\min}) / P_{aci\max}$ (3)

$$a_{Qi} = (V_{ac\max} - V_{ac\min}) / Q_{aci\max} \qquad (4)$$

Similarly, in order to regulate dc bus, simple voltage droop control scheme is implemented and the droop equation is

$$V_{dc} = V_{dc\max} - d_j P_{dcj}, \qquad j \in [1, n] \qquad (5)$$

Where $V_{dc\max}$ the maximum voltage output, 'j' represents total number of dispatching units of DC subgrid and the DC droop coefficient 'd 'can be expressed as

$$d = (V_{dc\max} - V_{dc\min}) / P_{dcj\max} \qquad (6)$$

However, for the analysis of power flow on TLBIAC community only ac frequency (f_{ac}) and dc voltage (V_{dc}) are considered because droop schemes floats (f_{ac}) and (V_{dc}). Based on loading conditions of both the subgrids AC and DC, power flow occurs in the HM. At steady state, both the loading conditions get equalized. Power flow does not depend on which subgrid is heavily loaded or lightly loaded. It concentrates only on the loading situation (LS) that, whenever there exist a difference in the LS, generates reference active power $(\Delta P_{TLBIACs})$ expressed as

$$\Delta P_{BIACs} = \frac{P_{ac} P_{dc\max} - P_{dc} P_{ac\max}}{P_{dc\max} + P_{ac\max}} \qquad (7)$$

The TLBIACs community implemented in the hybrid microgrid is of different ratings and with different switching frequencies. To attain global power sharing in HM, the objectives are

1. Avoiding overstress using single TLBIAC. To achieve first objective, the control objective is summation of reference powers of all the TLBIACs in the community is $\Delta P_{TLBIACs}$ and is proportional to their ratings i.e

$$\sum_{k=1}^{x} P_{kref} = \Delta P_{BIACs} \qquad (8)$$

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Subjected to; $\frac{P_{1ref}}{P_{1\max}} = \ldots . \frac{P_{kref}}{P_{k\max}} = \ldots . \frac{P_{xref}}{P_{x\max}}$ (9)

2. The next objective is leading role transition i.e whenever a power converter in the community fails to work, the role of faulted converter is taken by the any one of the converters out of remaining in the community.
3. The third objective is bidirectional power flow between the two sub grids during unbalanced load conditions and
4. The fourth objective is to attain the stability of the system without any communication delay during power interchange.

Performance of LDPIC

Implementing the proposed multilevel topology to K[th] BIAC including current compensator and LDPIC for power management is depicted in fig.3.

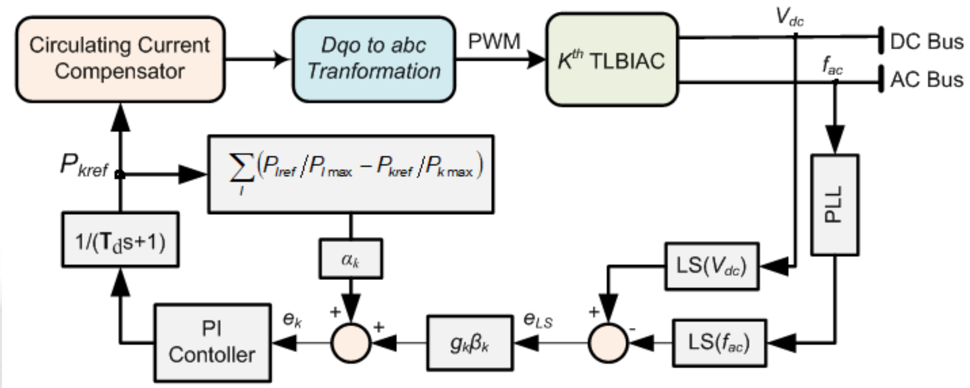

Fig.4. Control strategy for the proposed TLBIACs Community

The power reference generated from the localized distribution control using PI controller is send to the current compensator which drives the TLBIAC. To reduce switching losses, TLBIACs are chosen with large capacity. However, large capacity may have low switching frequency which results a control delay and requires high filter inductance for harmonic suppression of higher order. This affects the power interchanges and rise stability issues with improper design of current compensator. To triumph over these complexities, a suitable current compensator and in order to achieve the aforementioned objectives a LDPIC is designed and placed at each of the TLBIAC in the HM. In fig.2, it is depicted that, the converter community is configured with 'x' no. of TLBIACS. However, for easy analysis quantitatively the community considered to be consisting of three no. of converters and the power rating to be chosen is in the ratio of $P_{1\max} = P_{2\max} = P_{3\max} = 3:2:1$. Moreover, $TLBIAC_1$ is designed as leader and remaining two are followers.

For each of TLBIAC in the community functioning as either leader or follower, the consequent LDPIC anonymously provides power reference to the current compensator. Therefore, the Pulse width modulated gate signals were generated by the compensator drives the three level bridges. Hence, the real power flow through TLBIAC tracks the appropriate power reference. An LDPIC designed for *K*th TLBIAC for the first two objectives are

$$\left.\begin{aligned} P_{kref} &= G_d\left(K_{k1}e_k + K_{k2}\int e_k dt\right) \\ e_k &= \left[\alpha_k \sum_l \left(\frac{P_{lref}}{P_{l\max}} - \frac{P_{kref}}{P_{k\max}}\right) + g_k \beta_k e_{LS}\right] \\ e_{LS} &= LS(V_{dc}) - LS(f_{ac}) \end{aligned}\right\} \quad (10)$$

Where α_k and β_k are proportional gains, g_k is pinning control gain and for leader TLBIAC its value holds a non-zero constant, and e_k is the error generated by the proportional Integral controller (PIC) and in steady state whose value is zero. From the control diagram presented in fig.4, the PIC process two errors. The first error is information from neighbour TLBIAC and second error is localized information i.e $P_{lref}/P_{l\max} - P_{kref}/P_{k\max}$ and $LS(V_{dc}) - LS(f_{ac})$ respectively. The difference in error becomes zero, when HM reaches to equilibrium state. The control strategy for the proposed power converter includes exchange of information causing a delay while communicating each other in the community which indirectly slows down the system response and cause even

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oscillations in power. Hence, a delay term G_d is also included for accurate designing process i.e.

$$G_d = \frac{1}{(\tau_d s + 1)} \tag{19}$$

Where τ_d represents communication time delay, which helps to analyze the stability of the system. Therefore, it is important to consider the impacts of time delay on the system performance. Two points have to be considered while modeling the system. At first, for any TLBIAC in the community, the complete control structure is designed in two loops i.e inner loop as current compensator of high bandwidth with unity gain and outer loop as LDPIC, whose dynamics are studied. Secondly, behavior of HM due to AC and DC droop and power flow in the community.

Results

To attain global power sharing in HM, the proposed TLBIAC including LDPIC is validated in Matlab/Simulink software. For validating the results of proposed work, it is important to know the requirements such as DC bus voltage, AC bus frequency, ratings of TLBIAC in the community and their switching frequencies. In general, DC bus voltage selection depends on the type of applications i.e 24~48V is applicable for low power rating devices (electronic equipments), 230~240V for medium power rating devices such as ovens, washing machines, and dishwashers etc, and 380~750V suitable for electric vehicles, data centre's etc. However, in the proposed work, standard residential voltage in India i.e., 220V/50Hz rms with an amplitude of 220*1.414=311V is selected. In order to connect both the buses AC and DC and to guarantee the power exchange more than 311V i.e 311*2=622V should be considered as DC bus voltage. But in this paper, the level of DC bus limit to 700V and for any deviation ±10V should be considered. Therefore, DC bus voltage is selected as 710V as maximum and 690V as minimum. The system parameters to be considered to implement the proposed converter structure in HM for attaining global power sharing is presented in table.1. For proper power management, four cases i.e balanced power sharing, leading role transition, bidirectional power flow, system stability were considered and analyzed individually maintaining the voltage and frequency in stable.

Table: 1 System parameters

Parameter	**Description**	**Value**
V_{dc}	DC Bus Voltage	710V
f_{ac}	AC Bus Frequency	50Hz
V_{dcmax}	Maximum dc bus voltage	710V
V_{dcmin}	Minimum dc bus voltage	690V
f_{acmax}	Maximum ac frequency	51Hz
f_{acmin}	Minimum ac frequency	49Hz
P_{1max}	Power Rating of BIC1	6KW
P_{2max}	Power Rating of BIC1	4KW
P_{3max}	Power Rating of BIC1	2KW
K_p, K_i	Proportional, Integral gains in LDPIC	2, 800
$f_{1sw}, f_{2sw}, f_{3sw}$	Switching frequencies of TLBIACs	10KHz, 15KHz, 20KHz

Case1:

First case demonstrates the power sharing among the three TLBIACs during unbalanced loading condition by maintaining V_{dc} and f_{ac} stable shown in fig(1) and fig(2). For analysis purpose it should be considered that, both grids are of equal capacities and AC subgrid feeds the load approximately of about 12.84KW and DC subgrid is of 0.92KW. Hence, it is easy to know that AC subgrid is loaded heavy where as DC subgrid is loaded lightly.

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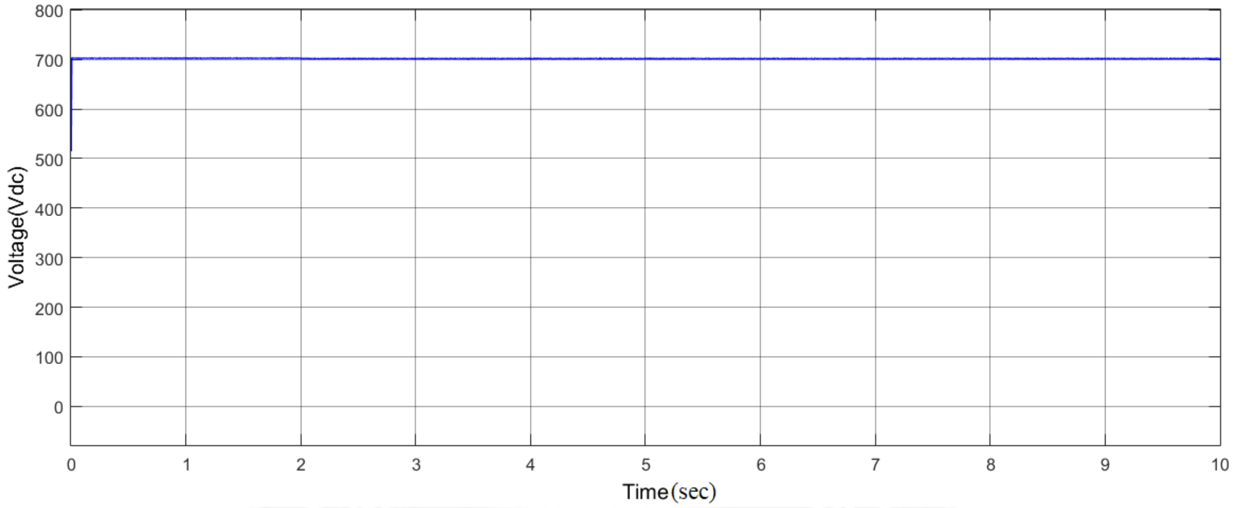

Fig. 5. DC bus voltage

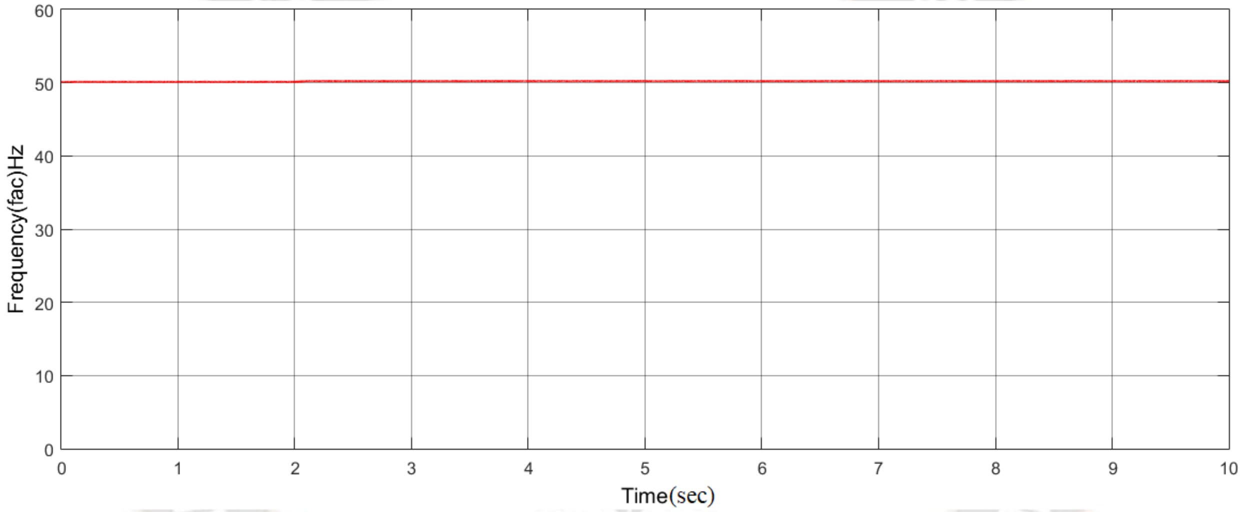

Fig. 6. Stable AC bus frequency

To balance the load between the two subgrids, and to transfer power from DC to AC subgrid the TLBIAC community should be enabled. $TLBIAC_1$ is triggered first, immediately both the subgrids converges the power at the same value i.e, 6.86KW is shown in fig(7) and $TLBIAC_1$ read the power as 5.97KW is depicted in fig(8).

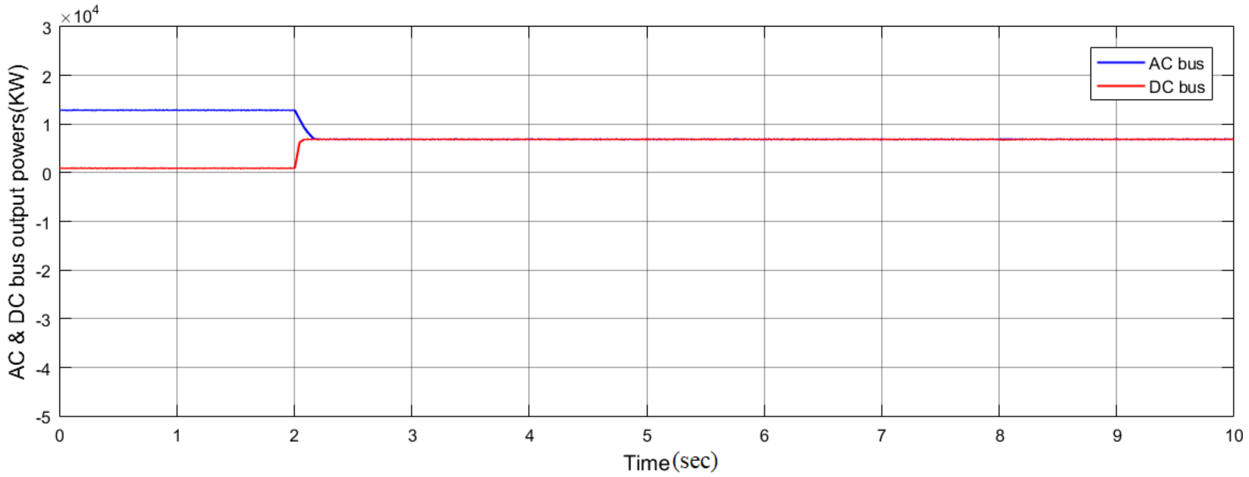

Fig.7. Output power at both the subgrids AC and DC

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Next, $TLBIAC_2$ is triggered ON to avoid overstress faced by $TLBIAC_1$, read as 2.39KW and the power through first converter drops to 3.58KW is shown in fig(8). However, summation of all powers that flow through the converters in the community is equal to 5.97KW. With regard to triggering of $TLBIAC_3$ same results can be obtained and the power distributed among all the three power converters i.e 2.99KW, 1.99KWand 0.99KW is shown in fig(7). Hence, replacing the two level with multi- level converter power can be shared proportionally among the converter community to attain global power sharing.

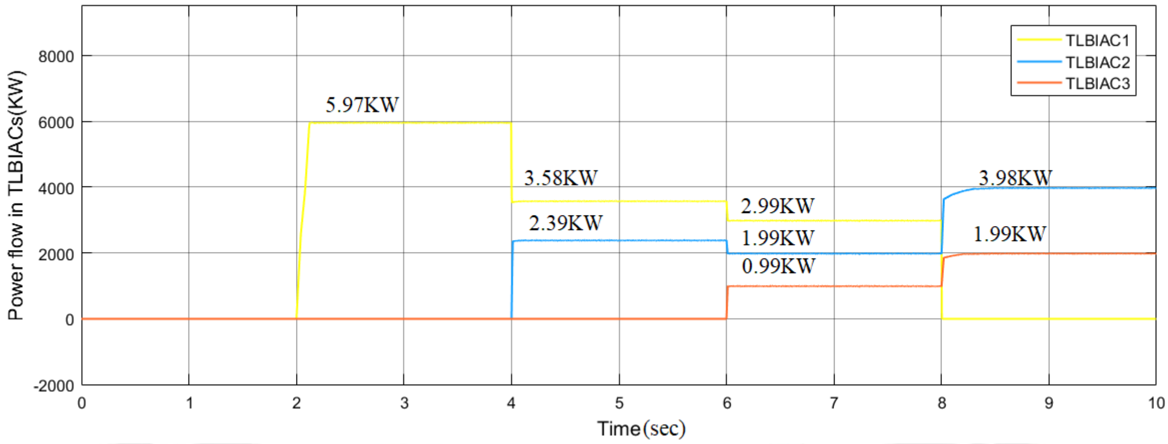

Fig.8. Power sharing among three converters and leading role during fault in first converter

Case 2

Case 2 explains the leading role taken by any other power converter during the failure of first converter in the community. When $TLBIAC_1$ is disabled, due to occurrence of fault, appropriate PWM signals and protective devices were turned off and the power immediately decreases to zero. However, any one of power converter in the community leads the leader role by communicating each other and the total power 5.97KW is distributed among the remaining two converters i.e 3.98KW and 1.99KW respectively is shown in fig(8). Thus, the second objective is achieved approximating the power ratio as 2:1. Hence, from the above discussion it is clear that replacing two level with multi level the system has strong fault tolerant capability.

Case 3

Case 3 explains the bidirectional power flow on TLBIACs community. Considering the state of normal operating conditions of all the power converters, load on both the subgrids were increased. Immediately, inversion of power flow takes place because of increased load in DC subgrid. When load in DC subgrid is high compared to load in AC subgrid, the power changes its direction and flows AC to DC subgrid. The powers can be shown as -3KW, -2KW, and-1KW in fig(10) and output power of both subgrids converge at 19KW shown in fig(9) maintaining V_{dc} and f_{ac} as stable. Whereas, in case of AC load increment compared to DC load regains its original power flow as positive and are shown as 2.9KW, 1.9KW and 0.9KW in fig(10) approximately in the ratio of 3:2:1 maintaining the output power as 30.8KW by both the subgrids shown in fig(9).From the above results it is clear that bidirectional power flow also occurs with replacement of two level with multilevel topology and designing proper LDPI controller.

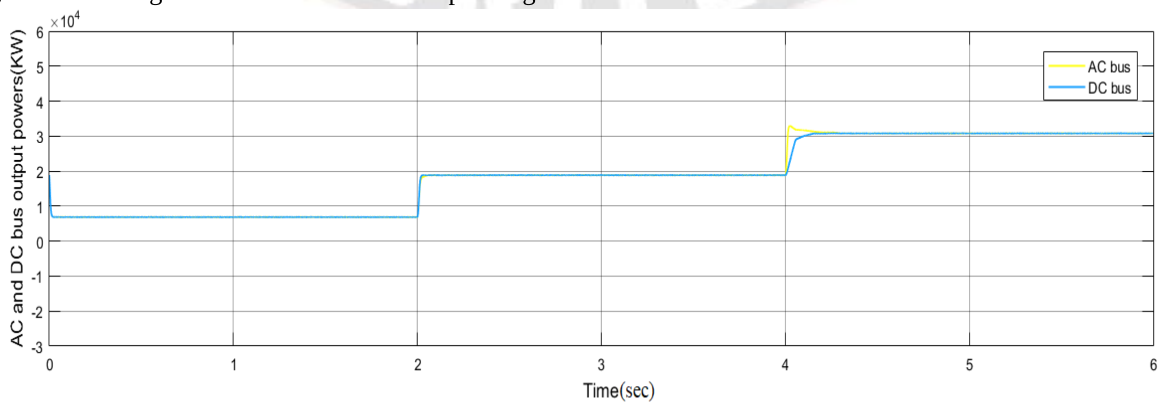

Fig.9. Output powers of AC and DC subgrids

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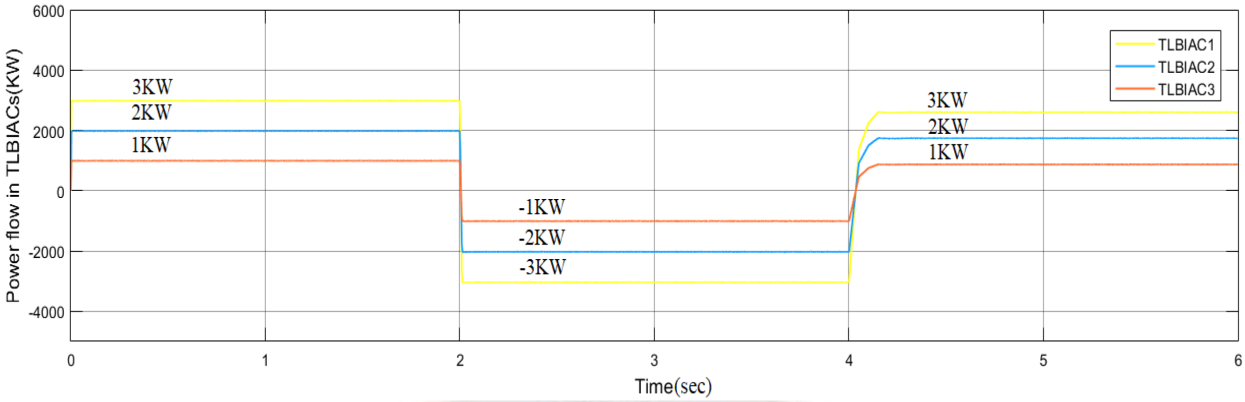
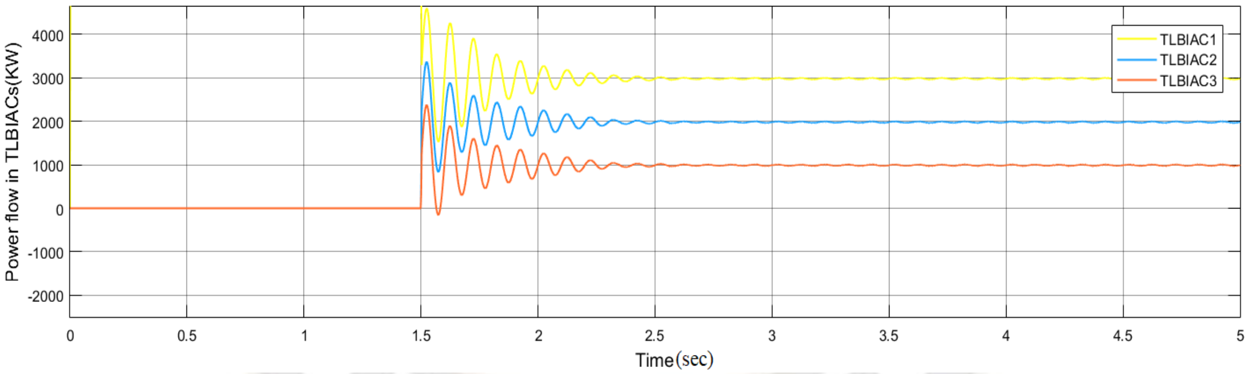


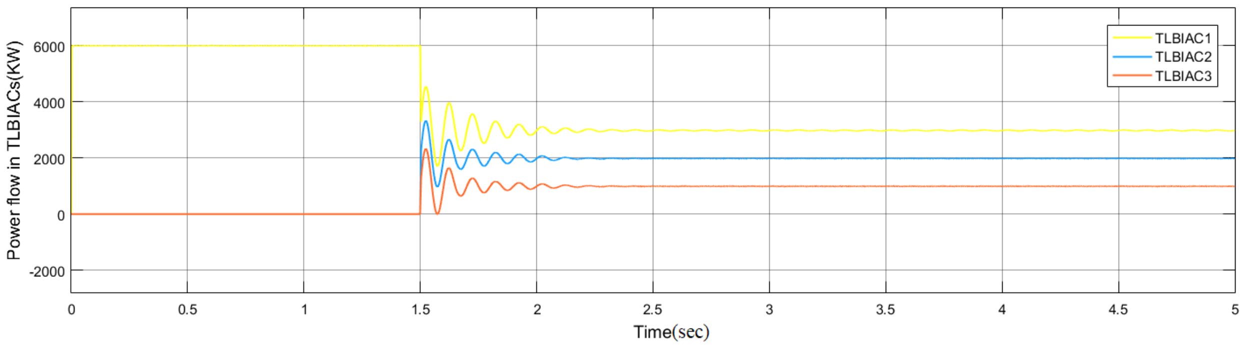
Fig.10. Bidirectional power flow in TLBIACs community

Case 4 Effect of Communication delay on system stability

From the power flow analysis of TLBIACs it can be observed that, a parameter known as communication delay τ_d affects the overall system stability. Hence, case 4 discusses about the system performance for various values of communication delays. Referring to case 1, $TLBIAC_1$ is enabled first, and remaining two converters in the community are at stand alone. When $TLBIAC_2$ and $TLBIAC_3$ are enabled, there exists a transient behavior of the system which affects the system stability producing power oscillations. Power flows using multilevel BIACs is shown in fig(11) for communication delay of 0.5sec,0.8sec and 1.0sec respectively. For τ_d =0.5sec the power maintains stability at 2.5sec and for τ_d =0.8sec the power reaches stability at 2.25sec where as τ_d =1.0 sec the system becomes unstable the limiting value of τ_d is 0.9.



(a)



(b)

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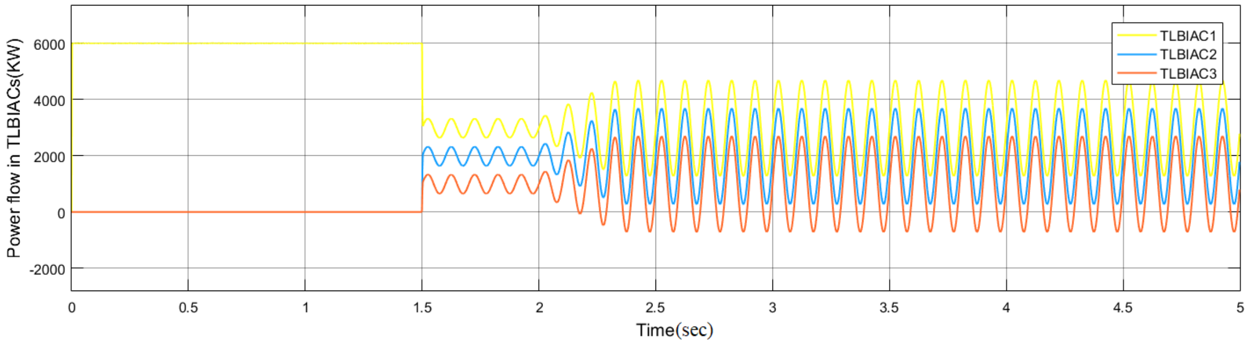

(c)

Fig.11 Power flows through TLBIACs for different values of (a) τ_d =0.5s (b) τ_d =0.8s (c) τ_d =1s

Conclusions

In this paper, a TLBIAC community with neutral clamped configuration is proposed and implemented to analyze the concepts of power sharing in HM. Each TLBIAC in the community is accompanied with a LDPIC to generate appropriate power reference. The TLBIACs in the community has shared the power based on their ratings approximately in the ratio 3:2:1, avoiding overstress and also exhibited successfully the property of leading role transition during the failure of any one of the converter. Moreover, bidirectional power flow is also achieved based on the loading conditions of the subgrid. A communication delay is also considered, which affect the system stability. For values of 0.5sec, 0.8sec and 1.0 sec of τ_d , the power through TLBIAC is observed and it is concluded that the value of τ_d beyond 0.9sec the system becomes unstable. For, the stability of system the value of τ_d must be less than 0.9sec. MATLAB/Simulink validated the proposed work to attain global power sharing.

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