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# A magnetically coupled multi-port, multi-operation-mode micro-grid with a predictive dynamic programming-based energy management for residential applications

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ABSTRACT

This paper presents the development of a residential micro-grid topology based on a combination of common magnetic and electrical buses. The magnetic bus interfaces two low voltage dc buses linking a PV and a fuel cell to a high voltage dc bus connected to a grid-tied single-phase bidirectional inverter. A battery is used to store the surplus energy of the system and stabilise the dc voltage of the fuel cell bus. A synchronised bus voltage balance (SBVB) technique is used to reduce the conduction losses and increase the soft switching operation range of the converters. To improve the maximum power point tracking (MPPT) performance and system efficiency, appropriate control techniques and compensation blocks are designed. The proposed micro-grid is able to operate in multiple grid-connected and off-grid operation modes according to a predictive 2D dynamic programming-based energy management. A mode selection and transition strategy is developed to select the appropriate operation mode and smooth the mode transition. A detailed study of the micro-grid including steady-state operation, small signal modelling, controller design, and energy management is presented. A prototype of the system is developed, and experimental tests are conducted for an energy management scenario.

## 1. Introduction

Over the past century, the average global air temperature at the earth surface has been raised to about 0.74 °C, which has generated serious concerns about the global warming and consequent environmental problems [1]. Some studies suggested that this is mainly caused by the excessive use of various fossil fuels, such as oil and coal. Therefore, the demand for environment-friendly sustainable energy sources has increased significantly over the past decades. The electricity generation as one of the major contributors to the environmental pollution is undergoing a fundamental change towards clean energy sources. In the residential sector, one of the major electricity users, renewable energy systems, such as solar, wind, and micro-combined heat and power (μCHP), are growing rapidly. In Australia, the share of renewable energies in electricity in 2014 was 13.47%, which is enough for supplying approximately 4.5 million average households [2]. The annual installed capacity of solar photovoltaic (PV) in the residential and commercial sectors has increased from 20 MW in 2008 to 1000 MW in 2015 [2]. This can effectively reduce the electricity bill of the households and contributes significantly towards the reduction of greenhouse gas emission. Residential micro-grids as a solution for integration of small-scale renewable sources into the grid have been attractive for research over the last decade. Hybrid renewable energy systems are considered as a solution to overcome the intermittency of renewable resources, and many multi-port converter topologies are proposed for energy integration [3]. However, most of these topologies cannot be used in residential applications due to the lack of required standards and safety features, poor flexibility and control, and limited range of processing power. In Australia, the provisions for the demand response and power quality modes are recently included in the Australian/New Zealand standard for grid-connected renewable energy systems (AS/NZS 4777) [4]. The multiple mode operation converters with configurable settings and energy management using PC and Ethernet are recommended [4,5] and currently are under development by some companies [6]. Therefore, there is a strong demand for more efficient, flexible, reliable and technically compatible topologies for residential micro-grids.

Research on the energy management of residential micro-grids mainly focused on the topologies, objectives, and methods. The majority of works are related to the demand–side management [7,8], off-line optimization methods [9,10] and online ruled-base power flow control techniques [11,12]. Other methods using fuzzy controllers and

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neural networks also have been reported [13,14]. Zhi et al. presented three control strategies for home energy management system namely, mixed integer programming (MILP), MILP with continuous relaxation and fuzzy logic controller and compared the results [15]. Among the optimization methods, dynamic programming attracted more interest as it can solve the problems with any type of constraints (linear or nonlinear, convex or concave, etc.) [9]. Nevertheless, none of the presented methods provides a device level study of the micro-grid topology and converters and their effects on the optimal energy management as provided in this paper. From a topological point of view, the proposed micro-grids are mainly based on a common dc or ac bus and multi-conversion configuration [13,16]. In contrast to the common ac bus, the dc bus is simple and more efficient and no frequency and phase control is required although it does not provide the isolation requirement in residential applications [17,18]. On the other hand, it cannot handle a wide variety of source voltages [3].

The third option in small-scale applications is using a common magnetic bus (multi-winding high-frequency transformer) which integrates the energies in the form of magnetic flux [19,20]. In contrast to the multi-conversion based topologies, employing the magnetic link can reduce the number of voltage conversion blocks and control complexity [3,21]. Consequently, the system efficiency can be increased, and the system complexity, size, and cost reduced [19,20]. Despite the advantages of the magnetic links, their design and development become highly complex with the increasing number of windings and conversion ports [3,20].Therefore, a combination of dc bus and the magnetic link is preferred in this research to utilize their advantages. In the proposed topology, low voltage sources such as PV, fuel cell and the batteries are linked to the common dc buses according to their voltage level and application. The dc buses are further linked to the high-frequency magnetic link through dc-ac converters.

To control the amount and direction of power flow between the ports through the magnetic link, a phase shift control technique is preferred due to its simplicity [19–22]. To link the low voltage sources such as PV, fuel cell and batteries to the common dc bus, boost or buck-boost converters are the most promising topologies [23–25].

In this paper, a micro-grid topology using a high-frequency magnetic link is introduced for residential micro-grid applications. The topology of the proposed micro-grid and the control circuits are presented in Fig. 1. The micro-grid is designed to supply a 4 kW residential load from combined energy sources of a PV array, a fuel cell stack, and a battery bank. The fuel cell stack is used as the backup energy source while the PV is considered as the preferred source to supply the load and possibly the grid. The battery is used as the energy storage device and also balances the voltage of the dc bus due to the slow dynamic response of the fuel cell. It also handles the quick start up which lets the fuel cell warm up. An electrolyser is considered as an optional load to generate the required hydrogen for the fuel cell and increase the systems flexibility and energy storage capability.

As shown in the figure, the micro-grid structure includes a triple active bridge (TAB) dc-dc converter which couples ports one, two, and three. Port one is a bi-directional port that transfers the power from the renewable sources or battery to the high voltage dc bus and further to the inverter, local loads and grid. The single-phase inverter links the proposed micro-gird to the main grid. It also operates in the rectifier mode to transfer the power reversely from the grid to the battery (using Ports two and four simultaneously) and stabilize the high voltage dc bus. The interleaved boost converter is used in Port three to step up the PV output voltage and utilize the maximum power point tracking (MPPT). The interleaved inductors reduce the current ripple and improve the MPPT performance and the PV panel efficiency. On the other hand, a bi-directional buck-boost dc-dc converter is used in Port four to control the charge and discharge of the battery.

In summary, as the main contribution, this paper aims to present design, control and energy management of a micro-grid topology based on the most recent standards of the residential renewable energy systems (AS/NZS 4777, IEEE 1547 and IEC 62109). Therefore, several control techniques and hardware features have been used to improve the system performance according to the required standards which make it distinct from previously reported systems. The applied improvements include:

- -Using a magnetic link to interface the micro-grid components which isolates the converter ports for safety requirements, increases the micro-grid flexibility and operation modes and reduces the control complexity.
- Using interleaved topology in the PV port which improves the maximum power point tracking (MPPT) performance by reducing the high-frequency current ripples and results in more stable MPPT, smaller size filter components, and wide input voltage range.
- Using a synchronized bus-voltage balance (SBVB) technique to reduce the root mean square (RMS) and the peak value of the currents in the windings of the magnetic link and switching devices which reduce the conduction loss. This also leads to an equal volt-seconds product on the windings which increase the soft switching operation range of the converters.
- Using a compensation block in the inverter control loop to reduce the low-frequency current ripple propagated from the inverter output and the ac bus to the high-voltage dc bus and further to the PV and fuel cell buses. This can yield higher performance MPPT and smaller size filter components.
- -The proposed micro-grid can operate in a large number of grid-connected and off-grid operation modes and different energy management scenarios compared to the previously reported systems.
- -A novel energy management based on the real-time data and long-term predictions of the PV generation and load demand using a 2D dynamic programming is proposed. The efficiency performance of the micro-grid components such as converters, transformer and battery loss is included in the optimization algorithm.
- -A mode transition strategy by defining a state transition diagram (STD) and bridging modes is employed to smooth the mode transition.

The performance of the proposed topology and the control technique is experimentally validated for an energy management scenario through energy distribution and cost analysis. As this paper is going to analyse both device level and system level control of the micro-grid, some details are ignored due to the page length limit.

The rest of the paper is organized as follows. The micro-grid steady-state operation is studied in section 2. In section 3, the controller design techniques and section 4, operation modes and energy management method of the proposed micro-grid are reviewed. The experimental test results are presented in Section 5 and conclusions in section 6.

## 2. Steady state operation of the micro-grid

The TAB converter is used to transfer the power between port one, two and three by introducing leading or lagging phase shifts between the high-frequency square waves (generated by H-bridge converters) applied to the windings of the magnetic link [19–22]. The high-voltage dc of bus one ($V_{b1}$), should be kept constant during the normal operation of the converter since a regulated voltage is required to supply the inverter and consequently output loads. The power transfer between ports two and one in the proposed TAB converter considering constant duty cycle at Port one and two ($D_1 = D_2 = 1$), can be found from [19] as

$$P_{21} = \frac{V_{b2}V_{b1}}{2n_{21}\pi f L_{21}}\phi_{21}\left(1-\frac{|\phi_{21}|}{\pi}\right) \tag{1}$$

where $\varphi_{21}$ is the leading phase shift of voltage of port two ($v_{t2}$) to voltage of port one ($v_{t1}$), $V_{b1}$ and $V_{b2}$ voltages of bus one and two