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# Multi-port Power Electric Interface for Renewable Energy Sources

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**Abstract:** In order to accommodate increasing energy demand from"more electrified" domestic and vehicular applications, simultaneous use of various renewable sources are encouraged. Multiple converters are commonly adopted to process the renewable power as a distributed power system (DPS). However, due to the loose structure of DPS, reliability and load/source regulation will degrade as compared to an integrated converter system. This paper presents the concept of Multi-port Power Electronic Interface (MPEI) for renewable energy sources. With a unified converter topology and highly integrated digital control system, MPEI possesses the inherent capability of both source disturbance rejection and load dynamics regulation. MPEI identification, modeling and design are treated in a systematic manner in this paper. Power stages and digital control system will be implemented for a five-port MPEI in this paper. Experimental results will be presented to prove the feasibility of system design methodology.

**Keywords:** Distributed power system (DPS), Multi-port Power Electronic Interface (MPEI)

## I. INTRODUCTION

Renewable energy sources are getting more attentions in a broad range of applications. With more "electrified" com-ponents in stationary and mobile applications, the demand for electricity has been increasing over the years. Different renewable sources are incorporated in both conventional power processing system and renewable source powered system to boost the power output. Applications like multiple-converter based distributed power systems have been reported in past literatures to deal with multi-source input, referring Fig.1. Most of such systems are based on local controller with com-munication capabilities or agent-based decision making mech-anism [5]-[7], among which wind generation is a typical and successful example.

However, if renewable sources are locally available to supply low to medium power range applications such micro-grid and critical industrial zones, conventional control system structure for DPS might not be suitable for such dynamic loads. With communication based control system, cost and reliability are the major concern in term of hardware implementation; software delay introduced by communication process is to further degrade the performance of such systems. Unified multiple input converter topology has the advantages of low cost, high power density and ease of management. There has been extensive research on multiple input converter system in recent five years which resulted in wide variety of topologies. Generally, multiple input converters can be classified into two categories: magnetically coupled converter (MCC) and electrically coupled converter (ECC). Based on the converter topology, flux addition and time domain multiplexing are used in magnetically coupled type to transfer energy from primary side of converter to the secondary. [8] Was one of the earliest versions of MCC using time domain multiplexing. [13][15][18][19][20][21][22][23] use bridge topologies which based on flux addition principle; power from different sources is transferred to the secondary by adding current from each conversion channel. MCC offers high power density and more flexible output voltage level since high frequency transformer and soft switching techniques are used; however, peripheral circuit for MCC is very complex and implementation of load sharing among different sources and energy storage elements is complicated[22](though time multiplexing controlled MCC is straight forward). Electrically coupled converter is usually implemented with non-isolated converter topologies, such as buck, boost and cuk. The power flow control of ECC is relatively straight forward and peripheral circuit for ECC is usually simple. Although ECC has less flexibility for voltage output, the modular structure and lower cost make ECC more favourable in variety of applications such as automotive. [9][10][11][27] use uniform converter cells to form multiple input converter system for both stationary and mobile applications; [12] combines different converter topologies together to form ECC as a front-end for utility grid applications. [17] summarizes variety of topologies and create a comprehensive review of multi-port dc-dc conversion.

However most of the systems mentioned above mainly deal with unidirectional power processing without stressing on modes of sustainable operation which is the unique feature of a multi-port system. Also, due to the fact that different renewable sources have their own dynamic range and supply of "fuel", characteristics of renewable source also has to be considered during the system design. Therefore, topology, control system design and modes of operation has to be considered through the design process.

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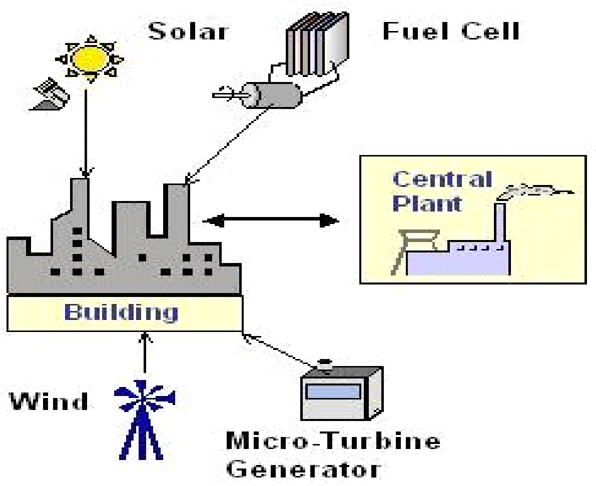
To remedy the disadvantages of the DPS and current multiple-input converter system, the concept of Multi-port Power Electronic Interface (MPEI) is introduced in this paper. Term”interface” is adopted here due to the fact that both ac and dc power can be processed by the system and dispatched quantitatively to desired port while the past literature all stress on dc-dc power conversion.

A five-port system is presented as an example. Integrated digital control system is proposed to achieve optimally controlled DC power flow, renewable source conditioning and satisfactory system response. Experimental results will be provided to proved the feasibility of system design.




## II. MULTI-PORT POWER ELECTRONIC INTERFACE

The concept of multi-port power electronic interface is address here: A Multi-port Power Electronic Interface (MPEI) is a self-sustainable multiple input/output static power electronic converter which is capable of interfacing with different sources, storages and loads, the integrated control system of MPEI enables both excellent system dynamic and steady state performance which renders optimal renewable energy harvesting, optimal energy management and optimal and economical utility grid interactions in a deregulated power market.

Figure 2 indicates the typical application of MPEI in harvesting and managing renewable energy sources. Different types of renewable sources, energy storages and conventional power sources are connected to the ports of MPEI. in forms of ac and dc power.

Similar to its counterpart at signal level, MPEI behaves like an information processing and distribution centre, which processes and dispatches information to desired terminals. However in power electronics applications, signal integrity and information security is not of concern as in signal processing system, but power flow control and conditioning.

## III. CIRCUIT TOPOLOGY

Topology selection is based on the actual system requirement; usually high frequency transformer-based bidirectional MPEI can provide high power density, isolation and flexible output voltage levels. However, complexity of supporting circuit lowers the reliability of the system.
Also, inherent current circulating and loss of voltage waveform problem [20] due to magnetic-coupling will need further design effort and components to overcome. Therefore, non-isolated converter topology is a more attractive candidate in MPEI system.

The circuit diagram for five-port MPEI is presented in this paper which interfaces with fuel cell, wind turbine, solar cell, battery and utility grid/island user. As indicated in Figure 3,

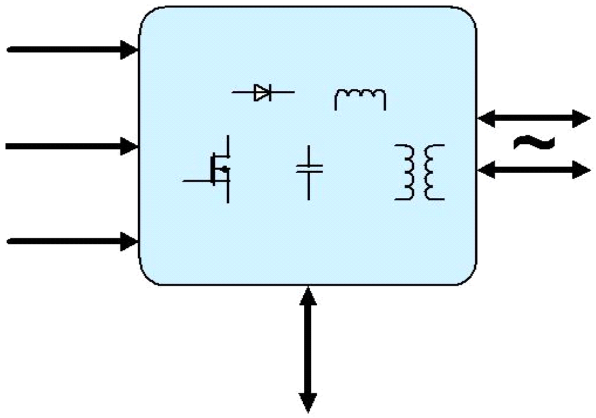


Fig. 2 Multi-port Power Electronic Interface

six-legged converter (using MOSFET) is used in the design, which form three unidirectional boost converters, one buck-boost bidirectional converter and one bidirectional PWM inverter/rectifier.

With standard phase leg switches, the system becomes very modular and easy to integrate. Due to the characteristics of interfaced sources, storages and loads, a higher voltage is needed on the system DC bus for inverter/DC-DC converter loads. Also low ripple continuous current should be taken from fuel cell as well as other renewable/storage sources since continuous current will impose less stress on source side. Therefore boost converters are used as the elementary energy conversion cells in MPEI system.

Battery serves as energy buffer as well as energy storage, therefore, battery converter is bidirectional: in discharging mode, boost converter discharge the battery to support load demand while in charging mode, buck converter is taking power from DC bus to charge the battery. The full bridge on the AC interface terminal can work either as inverter or as PWM rectifier based on the system operating modes as well as system component status.

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## IV. MPEI SYSTEM MODELING AND DESIGN

### A. System Level Analysis

As a power interface, MPEI does not store energy; renew-able or conventional power is optimally harvested and power flow will go either to energy storage or to ac port for grid and island user. Therefore, power processing in MPEI have two stages: preconditioning and load conditioning. Therefore, an intermediate goal exists in MPEI as to achieve a solid voltage or current DC-link to supply downstream converters.

The MPEI system can be further partitioned into front-end converter system as source converter and load-end converter system as load converter. In this paper, to simplify the analysis, four dc-dc converter is treated as source converter while single phase inverter which interface with ac interface is treated as load converter.

Another fact is that the ac interface does not necessarily operate with the same frequency as the dc interfaces due to different power capacity, therefore, partition of subsystem is required for convenience of system modeling. As indicated

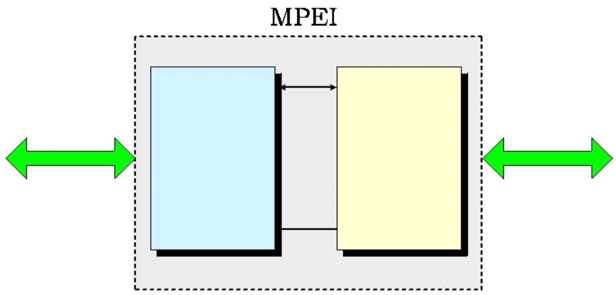


Fig. 4. Source and Load subsystem

### B. MPEI system analysis and modelling

As illustrated in the previous section, MPEI system is partitioned into load and source converter system for convenience of analysis and each subsystem can be modelled and characterized. To study MPEI system stability, Middle brook's criteria can be used to ensure small signal stability. Equation 1 indicates the criteria for asymptotic stability of a voltage controlled system by study the subsystem impedance, $Z_o$ for output impedance of source converter subsystem and $Z_i$ for load converter subsystem.

The stability is ensured is the Eigen value of the subsystem is located in the left hand side the imaginary axis. Since the source converter subsystem is featured with load sharing capacity, during operation, at least one converter need to be voltage-controlled to ensure the operation of downstream inverter. The $i^{th}$ row corresponds to open loop small signal control to output transfer function of $i^{th}$ converter with disturbances from other operational ports. If port-1 is selected by the system to operate at voltage-mode, the open loop control-to-output transfer function will be the transfer function of the very port converter plus the disturbance from other ports. Therefore, interference from other non-voltage-mode ports has to be considered in the control system design.

### C. Integrated Control System Design

The integrated control system structure is proposed in Figure 6., where $G_{id}(s)$ is input current-to-control transfer function; $G_{vi}(s)$ is output voltage-to-input current transfer function, $F_m$ is PWM modulation gain, $C_i(s)$ is current controller; $C_v(s)$ is voltage controller; $L_i$ is adjusting block for load sharing control; $H_i(s)$ is current transducer gain; $H_v(s)$ is voltage transducer gain. The cascaded control structure taking voltage controller output as the internal reference for the current controller to form average current-mode control(ACM) for each controller channel[1][2][3][4]. Since output power of each source has to be regulated and inductor current has to be regulated directly/indirectly for load sharing purposes.

Therefore, ACM control is one of the best candidates for local control. The common target of multi-port front-end is to keep DC-link voltage at a constant value; output voltage (DC-link) voltage is sensed and fed back to compare with the reference voltage, the voltage error is fed into voltage controller of the system and current controller reference is generated. Programmed current reference signal is scaled by adjusting block $L_i$ and fed

### D. Modes of operation

Taking the advantages of energy storage and controlled direction of power flow, MPEI can harvest energy and save for emergency use. Three modes has been defined for MPEI in sustainable mode of operation: generation mode, emergency mode and recovery mode. paper[9] explained in details on the emergency mode of operation where a three-port MPEI is used as a UPS system.

In generation mode, MPEI harvests renew-able energy and saves in energy storage as well as supplies ac load; in recovery mode of operation, renewable sources are used to back up the state of charge in energy storage such as battery and multiple sources are used if recovery of energy storage is an immediate task. Transition between the modes are event-based, the state machine of modes transition is shown in Figure 7, availability of renewable sources, state of charge in energy storages, power demand at load-end, utility line status and human input are used to make the mode transition decisions.

Therefore, with base power provider (fuel cell), renewable sources (wind and solar), energy storage (battery) and utility grid/island user. MPEI is operating in such a way that renewable energy are always optimally harvested and economically used, base power is always available, state of charge in energy storage is always above a safe level for emergency use. Therefore, MPEI can be on-line all the time, always provide sufficient power to user and generate zero emissions, which is a sustainable way of operation.

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## V. EXPERIMENTAL RESULTS

Experiment is conducted with two sources: fuel cell and battery. A 1.2KW prototype is built and some transient/steady state test is done. Current/power sharing based on fuel cell status and battery state of charge (SOC) is shown in Figure 8, current on fuel cell and battery port is kept being adjusted during the whole process to secure a fast system start as well as over discharge protection of battery[9].

During the first section of fuel cell start-up, battery SOC is high, fuel cell current reference input will be adjusted to a very small value, so that the effort of outer voltage loop vanished to fuel cell converter, fuel cell converter is equivalently working on single current loop control(Blue); battery channel is connected to DC bus with current-mode control, whose inner current loop limit is set at maximum allowable current out of the system.
Current mode control is known to have good transient response to load variation and input disturbance rejection, therefore, battery is taking care of all the load transient in those operation modes.

When battery SOC is low and load demand is still critical, fuel cell output current limit will be scaled up to avoid excessive discharge of battery and the current drawn from battery is naturally going down(in Fig. 8 active current sharing section). Emergency mode of operation is shown in Figure 9. Once the line voltage collapses, MPEI can detect the transition and goes to emergency mode of operation.

Battery channel (blue) is supplying full load at the beginning and fuel cell converter is warming-up with little load applied (section one on the left); during the second state, fuel cell is working to supply nominal load and charging the battery with 8A of current; in the power peaking state, fuel cell and battery are sharing the power to the load, the current reference of fuel cell converter is set to be the same as the battery converter which is indicated by the third section in Fig.9; in state four, on the presence of constant load demand, fuel cell has to supply the load all alone without battery (battery SOC too low).

As shown in the waveform, all the modes of operation are fully functional and smooth transition was achieved between the operation modes.

## VI. CONCLUSION

The paper brought up a new concept of Multi-port Power Electronic Interface for high power density, multi-renewable source application. Circuit topology and integrated control system structure is proposed and controller is designed based on small signal model. System is tested under 1.25KW of power and satisfactory results have been collected.

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