Chapter 2 : Literature Review

2.1 Distributed Energy Sources

The distributed non conventional energy resources such as wind generation, solar, hydro, fuel cell and similar other supply-side technologies are required to mixed together to suffice the energy demand to atleast small localized places. The control, communication and power electronic devices needs to be interfaced together so that the non-conventional energy is properly integrated for the appropriate running of the DC Nanogrid and Microgrid. Most of the renewable power sources rely heavily on power electronics and control strategy for their efficient usage and energy management. Modular technology imposes the studies on interleaved and multilevel power converters in power electronic domain for flexibility and portability aspects [26].

The DC microgrid connected to small local power units comprising of solar photovoltaics (PV) and wind turbine and a battery bank can serve a small community located in remote places. The photovoltaic energy is DC in nature and therefore it can directly be used for DC loads such as light emitting diode (LED), DC motor, fans and several other electronic gadgets as listed in table 1.2. The statistical increasing demands in computers, mobiles, LCD screen and network systems has made a large market in power industry [27].

The home appliances which generally contains power electronics makes them natively work on DC and they constitute high percentage of the loads and this results in lowering the cost of the system by 20% [28]. In this work the Photovoltaic module’s output power is regulated
using two DC\DC boost converters in parallel topology. In this work, it is also shown that how the PV modules interfaced with closed loop paralleled boost converter performs under irradiance variations. Solar energy is abundant and pollution free may be the future power for sustainable development.

2.2 Solar Energy

The choice of photovoltaic energy for applications in residential use is for three reasons; firstly Sun is the vital source of energy for every living species and it is abundantly available in nature. Secondly the photovoltaic module output voltage is low and thirdly load side DC appliance operating voltage is also low. The solar energy is extracted from the solar module by exploiting the photon’s energy present in the sunlight. Several stringed photovoltaic module form arrays which results in the generation of energy from a few watts to megawatt for solar power plant. The arrays mounted in appropriate angle, generally to longitude coordinates of the place so as to output maximum solar energy. The output power of the solar module is DC and a power conditioning system (PCS) is required for proper distribution and utilization.

2.3 Operation of photovoltaic module under varying irradiance and temperature

Solar cells are large PN junction diodes which converts the energy in sunrays to electric power. It is the basic power generating unit stringed together to form a PV module of high power. The photons present in sunrays excite the electrons from ground state to conduction
state in P-type semiconductor. When these excited electrons move in field region, they acquire electrical energy which is converted to current and voltage form to perform work. The basic electrical schematic of a solar cell with its parasitic resistances is shown in Figure 2.1.

![Figure 2.1 Schematic of solar cell with its parasitic resistances](image)

The relation between output current and voltage is given by equation (1.1)

\[
I = I_L - I_0 \left[ \exp \left( \frac{V+R_sI}{nV_t} \right) - 1 \right] - \frac{V+R_sI}{R_p} \ldots
\]  

(1.1)

where \(I_L\) and \(I_0\) are photon generated and reverse saturation current respectively [29]. The \(n\) represent ideality factor of the cell, \(R_s\) and \(R_p\) are parasitic series and shunt resistance respectively. \(V_t = \frac{N_skT}{q}\) is thermal voltage of the module with \(T\) representing temperature of the P-N junction. \(N_s\) represents the number of series connected cells and \(q\) and \(k\) are the electron charge and Boltzmann constant.

The two major factors affecting the power generation in photovoltaic module are irradiation and temperature. The impact of both factors is depicted in figure 1.3. As a result, this situation creates a challenge for researchers of power electronics and control to find an optimal
solution to it. There are many algorithms related to maximum power point tracking (MPPT) available, but they are efficient at only single condition.

Figure 2.2 Impact of irradiation and temperature on PV power output

A hybridized kind of MPPT is required, which can be efficient at all kinds of weather condition. However, in this work the focus is on aggregation of power from different available DC renewable resources to run DC load appliances as given in section 2.4 and not on efficient power tracking of the power modules.

2.4 DC Microgrid for DC appliances

The low power appliances for use in Korean residents are given in Table 2.1 which can be run on DC voltage bus of 48 V standard [30], and it supports the DC micro-grid as a feasibility study of the DC electrical distribution system.
<table>
<thead>
<tr>
<th>DC domestic Load</th>
<th>DC current consumption (A)</th>
<th>Total power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three LCD TVs</td>
<td>8.88</td>
<td>639</td>
</tr>
<tr>
<td>Refrigerator/Freezer</td>
<td>7.83</td>
<td>188</td>
</tr>
<tr>
<td>Two Video Game Player</td>
<td>8.13</td>
<td>390</td>
</tr>
<tr>
<td>Monitor</td>
<td>6.25</td>
<td>150</td>
</tr>
<tr>
<td>Desktop Computer</td>
<td>5.00</td>
<td>120</td>
</tr>
<tr>
<td>Lighting, LED</td>
<td>12.50</td>
<td>300</td>
</tr>
<tr>
<td>Mixer</td>
<td>4.17</td>
<td>100</td>
</tr>
<tr>
<td>Can Opender</td>
<td>4.17</td>
<td>100</td>
</tr>
<tr>
<td>Ceiling fan</td>
<td>3.13</td>
<td>75</td>
</tr>
<tr>
<td>Two Laptop</td>
<td>2.08</td>
<td>100</td>
</tr>
<tr>
<td>DVR w/Cable Box</td>
<td>1.83</td>
<td>44</td>
</tr>
<tr>
<td>Three DVD Player</td>
<td>0.71</td>
<td>51</td>
</tr>
<tr>
<td>Wireless router</td>
<td>0.29</td>
<td>7</td>
</tr>
<tr>
<td>Three Cell Phone Charger</td>
<td>0.17</td>
<td>12</td>
</tr>
</tbody>
</table>

Note: LCD: Liquid Crystal Display, TV: Television, LED: Light Emitting Diode, DVD: Digital Video play

As house loads, we consider as an air conditioner, a refrigerator, a washing machine, lighting and a television in each house. There is potential of cost competitiveness and energy efficiency in these types of DC loads. The absence of harmonics, low power factor and total harmonic distortion in DC makes it more efficient for home appliances operating at 48 volt supply. For a same set of AC and DC loads in a residence, it was found that DC consumed a 140kWh / month less than an AC load [20]. DC renewable energy resources could be much more readily incorporated into a premise DC bus. Doing so would eliminate conversion losses, each of which saves between 2.5% and 10% of the developed energy [31]. In addition, power quality and voltage stability are also advantages of this low voltage DC microgrid.

### 2.5 Control Schemes for Modular DC Converters

In this research work, the problem addressed is about the power sharing among the paralleled DC/DC converters. This application in distributed renewable energy sources is having a high potential, mainly in the area of photovoltaic power plant for residential applications. Recently
there is a lot of work going on to finalize the standards for the DC bus voltage. For DC microgrid residential utility, the standard choice of DC bus is 24-48 V.

Modular DC\DC converters can be potential candidates in harnessing the renewable power if they are systematically organised in suitable pattern and controlled with advanced controller accompanied with energy management algorithms. The available control schemes in literatures [32] are represented in Figure 2.1.

![Figure 2.3 Classification of Parallel Schemes](image)

Parallel methods are broadly categorized in two groups, namely droop method and active current control methods. Their basic principles, origin and applications are discussed in brief and details are available in given literature in Figure 2.1.
2.5.1 Droop Method

In droop method, as the load current increases the output voltage droops. This method is dependent on the impedance of parallel modules for the realization of the current distribution between the modules. There are five different possible droop schemes and their description is available in literature as shown in Figure 3.1. This method is easy in implementation without the any communication channel between the parallel converters. Its current sharing accuracy is poor at the cost of voltage regulation.

2.5.2 Active Current Control Method

An active current control technique consists of current programming methods and control structures. There are atleast half a dozen of current programming methods and three control structures and their details are found in literatures as shown in figure 3.1. The different combination of these control structures and current programming methods give rise to more than ten potential active control schemes. This method includes additional loops for the implementing in different applications. The control schemes used in hardware implementation in this work is current mode control method.

2.6 Study on Applied Control Methods on Parallel DC Converters
Hedel in 1980, [44] proposed on high density parallel DC\DC converters and after that the interleaved DC\DC converters have found lots of applications in distributed power-supply systems. Since then several interleaved isolated and non-isolated topologies of basic DC\DC converters are proposed and their design methodology is discussed. Siri et al, in 1992, [45] compared the two techniques for control of current distribution, namely the master-slave control (MSC) and central-limit control (CLC). The control approaches were applied on two parallel buck converters. The MSC technique with maximum current limit (MCL) on the active converters always kept their output currents at optimum value, in additions the system’s reliability increased and fault-tolerance design also improved. However, the MSC alone could not avoid the current overshoot during transient state, which may result in shortening the converter’s lifetime. In addition, the MCL with MSC results in current undershoot during step-load variations and hence undershoot in output voltage.

In 1993, Wu, R.-H. et.al, [46] investigated the control of three parallel forward DC\DC converters and discussed about the superiority of current balance control. In his work, four cases, namely different output resistances, different feedback gains, different voltage references and different transducer output voltages were considered. It is concluded that both analytical and experimental results based on the current balance controller provided a good adaptability to the parameter variations and load-current sharing. However, the voltage regulation is not discussed in detail, but with the difference of 10% in output voltage references of the converters the load-current sharing was performed and the load-current unbalanced could be suppressed.
In 1994, Issa Batarseh et al., the current-sharing control technique for the parallel-connected DC\DC converters without remote-sensing is proposed [47]. It ensures the even current distribution throughout the specified load range with the use of an independent proposed control circuit. In his work, it was demonstrated that even the droop method using the limited DC gain of the voltage compensator and the load dependent reference voltage could not achieve the near-uniform current distribution. It was concluded that droop control methodology alone could not provide even current sharing if the output voltage regulation is a deviation of less than 3%.

In 1995, Siri, K. et.al. [48] carried out the study on evaluation and analysis of parallel connected DC\DC converter’s current-sharing control with taking into account the cable resistance. In this paper a better current-sharing control, namely the Central-limit control over the traditional master-slave control is discussed. It concluded that the stability of the current-sharing didn't depend merely on the methods of current sharing, but also on the converter’s output cable resistance. However, the cable resistances discussed in this work do not differ by large in case the DC\DC converters are placed at different locations. J. Rajagopalan, et al., proposed the design of the current share compensator and the effect of it on the system output impedance is analyzed.

In 1998, Tuladhar. A and Jin. K, [49] proposed a novel control technique for the operation of parallel DC\DC converters without any control interconnections for load sharing in distributed power supply system. This technique uses the frequency droop mechanism and real power propagation in a DC network. In his work, three buck converters of the same power rating were modelled. With three different cable resistances, the system could adjust
the voltages of the individual converters and achieve the proper load sharing. However, the current overshoot and settling time were high and in case of converters of different power rating, the current sharing differed by large value while voltages differences were negligible.

Byungcho Choi in 1998 his work on the comparative study of three paralleling schemes for DC\DC converters for distributed power applications. First paralleling scheme is limited to the systems for fixed number of DC\DC converter modules. Second scheme is suitable for applications where flexible number of modules suit the output power variation. Third scheme is applicable for redundancy and fault tolerance against any converter’s component failure. It also presented the rules, making an appropriate choice of DC gain with a tradeoff between the steady-state error and current sharing. V. J. Thottuvelil et al., in 1998 included both the democratic and master-slave current sharing mode on the paralleled converter systems. In the stable current-sharing loop if the system is unstable, output currents in phase and if load voltage variation still exists, then analysis of these could be a significant clue in stabilizing an unstable system [50].

In 1999 Shiguo Luo, discussed about the several methods for paralleling power converters, broadly, two major ones are active current-sharing and Droop method. These methods provide valuable insights in designing parallel system. It presented a comprehensive study on the prominent features of the dominant paralleling schemes and verified the same by simulation of two-paralleled buck converters [32]. In 2002, J. M. Guerrero et al., used the charge control methodology to paralleled DC\DC converters [51]. In this approach, the integral of the inductor current reaches the reference value and accordingly a PWM with
fixed frequency switching is generated. By this method high line disturbance rejection, low-ripple current, robust against load variations, uniform current distribution was achieved.

In addition, it was simple to implement. In 2004, K. Siri et al.,[52] used the current mode method, share-bus DC\DC converters to power the topology of parallel-input series-output (PISO). In his contribution, he used the voltage regulation controller and current limiting controller. Both simulation and experimental outcome validated the uniform voltage distributed among the PISO topology and resulted in 49% to 80% conservation of energy. The solutions to the issues in load-sharing control and tracking the maximum power point of the solar array in Parallel-connected converters interfaced with PV systems can be found in the research paper [54],[55]. Yuehui H. et al., [55] presented a simulation result of three parallel schemes for current sharing. The three parallel schemes were (i) Connecting Thevenin sources in parallel, (ii) connecting one Thevmin with many Norton sources in parallel and (iii) connecting Norton sources in parallel. Each schemes pros and cons in terms of expansion, dynamic performance, current sharing accuracy and regulating capability were discussed.

In 2009, Wu Chen et al., proposed a general control strategy for parallel-series systems in which the output voltage control loop is decoupled from sharing control loop [56]. The three modular architectures enjoy full merits and no external controller is needed to co-ordinate the sharing control for the individual converter. The DC\DC converter is the backbone of DC microgrids and their various topologies along with load sharing and a power management mechanism has potential to sustain the energy demand for remote places. In the next chapter,
a simulation work using the droop method concept and PI tuning with PSO algorithm is discussed.

In our approach a parallel topology of two low cost DC\DC boost is used to extract power from two similar photovoltaic modules at small power scale. The load tested with this system is a resistive load. The control technique adopted in this work for power contribution from both DC\DC boost converter in parallel configuration is current mode control. A detailed study of this control technique is presented in chapter 3. However, apart from photovoltaic modules, there are a variety of distributed renewable energy resources that can be interfaced with this system to form a low voltage independent operating DC microgrid. The converters designed here are of low power. However, the power rating of these converters and its number can be scaled up as per the energy demand while keeping the same control strategy used in this work with additional auxiliary safety circuits to protect it from high power interference.