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A Review on Secondary Control Methods in DC Microgrid

*R. Dadi *, K. Meenakshy, and S.K. Damodaran*

Department of Electrical Engineering, Government Engineering College, Thrissur
APJ Abdul Kalam Technological University, Kerala, India.

Abstract- *DC Microgrid is turning out to be more popular due to its appealing features such as high efficiency, excellent power quality, low cost and controllability. As the control strategies plays a key role in achieving the desired objectives such as power quality, power sharing, voltage regulation and efficiency. It is necessary to understand the classification and operation of control strategies in DC microgrids. From the control point of view, the traditional droop control methods are commonly employed for regulating proportional load sharing. However, depending on the primary control makes it challenging to maintain stable and coordinated operation in terms of maintaining both the voltage regulation and load sharing accuracy simultaneously in DC microgrids. So to avoid the trade-off in voltage regulation and power sharing accuracy, secondary control layers need to be introduced in the control structure. In this paper a review of primary control and secondary control methods (centralized, decentralized and distributed control) were discussed in detail with the classification along with the advantages and shortcomings of the control methods.*

Keyword—DC microgrid (DC-MG), decentralized control, distributed control, secondary control.

1. INTRODUCTION

DC Microgrid has gained popularity in recent years due to the availability of renewable energy sources and absence of the rectification and inversion phases, making it possible to integrate Distributed Energy Resources (DER) [1] and Energy Storage Systems(ESS) more efficiently [2]. The distributed nature of the generation allows developing microgrids which includes the control and coordination of distributed generation (DGs) and ESS, to maintain power balance between sources and loads. Because of their superior efficiency, increased stability and reliability, DC-MGs are viewed as a viable option for various applications [3]. It also provides consistency with respect to consumer loads as it interfaces with numerous renewable energy sources and energy storage units. In DC microgrids, depending on the functions to be performed the control structure is segregated into three layers as follows:

- Primary control layer: It is composed of basic droop and converter control loop. It can provide either voltage regulation or current sharing accuracy. Primary control is basically considered as decentralized control.
- Secondary control layer: In addition to primary control, secondary control layers are added to the system which will provide reference to the primary control for providing proportional current sharing and voltage regulation simultaneously. Based on the availability of communication links, secondary control layer is again classified as centralized, decentralized and distributed control methods.
- Tertiary control layer: Tertiary control is an addition to the primary and secondary control layers which provide control signals to the secondary control to resolve the energy management and power dispatch problems in microgrids.

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*Corresponding author: E-mail: ramudadi@gectcr.ac.in (R. Dadi)
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The control methods in DC microgrids based on the communication link can be categorized as follows:

1) Centralized control method: A central controller is used to control the distributed generation units and information carried through high bandwidth communication links [4].
2) Decentralized control method: The DG units are controlled without any communication link, by making autonomous decisions based on the available local parameters.
3) Distributed control method: Each unit controller communicates with the others through a shared bus. This control utilizes a digital communication link.

The centralized method utilizes High Bandwidth Communication links (HBC). Though it provides better performance, it suffers from Single Point Of Failure (SPOF) i.e. in case any communication failure occurs then entire system operation will be effected adversely. In the second control strategy, the controller just requires knowledge about local variables. Communication happens only between nearby converters in the third control method. In a DC-MG, several control problems are existing such as precise load sharing, voltage regulation and circulating currents between the parallel operating sources. In [5] a repetitive controller is used in series with the current controller to generate the duty cycle so as to reduce the circulating current and voltage regulation at a cost of current sharing accuracy. A good controller should assure system stability while also attaining the required objectives. The traditional droop is a standard controller that is often used in DC-MGs. The functionality of a droop controller relies completely on the droop gains, which are adjusted to be sufficiently greater in relation to the line resistance. Large droop gain values on the other hand, result in precise current sharing at a cost of voltage regulation. When the droop gains were set to low, the voltage regulation will be in acceptable range but the power sharing accuracy suffers substantially. As a result, there always exists a trade-off in precise load power sharing and voltage deviation. Rest of the paper is organized as follows. In Section II, primary control methods in DC-MG are discussed. Section III explains the limitations of traditional droop control method in DC microgrid. In Section IV, secondary control methods in DC-MG are given. Section V gives the conclusion.

2. PRIMARY CONTROL METHODS IN DC MICROGRIDS

The primary control layer of a DC microgrid is made up of inner loops and droop control as represented in Fig.1.

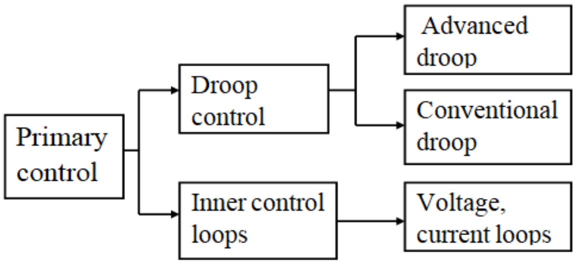

Fig. 1: Classification of primary control methods

2.1. Inner loop

Though we have different kinds of DC/DC converters, the control modes can be divided to two types: current and voltage control mode. The DC/DC converters voltage control mode provides reference voltage and acts as a controllable voltage source. Under current control mode the converter works as a controlled current source. The current output is adjusted to match the reference given. Fig.2. represents a single voltage loop as the converter operating in voltage control mode. Voltage controller provides duty cycle as the output. The inner current loop is shown in Fig.3. where the duty cycle is produced via a current regulator. Cascaded loop is shown

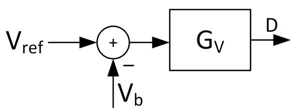

Fig. 2: Voltage loop

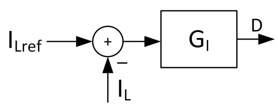

Fig. 3: Current loop

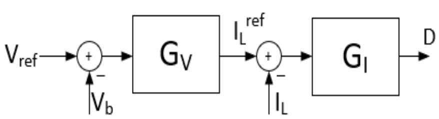

Fig. 4: Cascaded loop representation

in Fig.4. where for a given reference voltage, voltage controller G_v gives the inductor current reference and current controller G_I gives switching signals at its output.

2.2. Droop control

Voltage droop control is extensively used since it does not require communication lines. Droop control is commonly defined by introducing a virtual impedance to the present system. The virtual impedance is an ideal parameter as it neither influences the operating condition (temperature) nor it produces power loss. This virtual resistance is also termed as the droop gain or the droop coefficient. The droop control method improves device modularity and efficiency as a decentralized control mechanism for the realization of desirable power sharing. The main shortcoming of the typical droop control method is that it reduces the precision of load current sharing. As the converter voltages may not be same because of the drop in voltage due to line resistance value, the accuracy in load current sharing is reduced. It also suffers from reduced bus voltage to its reference under larger droop gains.

2.3. Advanced Droop control

In addition to classic droop methods, some advanced methods are also examined to look into their performance. Fig.5 represents the classification of advanced droop control methods.

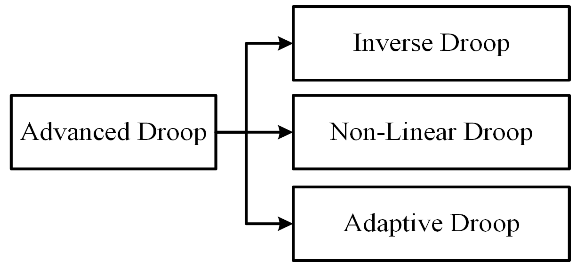

Fig. 5: Classification of advanced droop control methods

1) Inverse droop control

An inverse-droop control is used to offer power sharing for the series-input and parallel-output DC/DC converters, which includes input voltage and output current sharing [6]. The implemented control method raises the voltage reference of output as the load increases.

2) Adaptive droop control

To achieve successful load sharing, a droop method that regulates the reference voltage is suggested in [7]. However, this method only quantifies load sharing across sources with similar ratings, the sources of different ratings are not considered. A gain-scheduling approach was suggested in [8] that can achieve relatively better voltage control and load sharing. It is made possible by using a droop gain that varies during its operation, rather than merely choosing a high droop gain which leads to poor voltage regulation or choosing a lower droop which leads to poor load sharing. This approach requires analyzing the voltage error under different loading conditions with different droop gains and then it determines a specific relation between the droop gain and load condition.

3) Nonlinear Droop control

A nonlinear droop based control method was suggested in [9] where the droop coefficient is a factor of converter output current. As the load increases, this method will raise the droop coefficient. It also resolves the trade-off in traditional droop techniques [10]. As represented in Fig.6. an adaptive droop based non-linear

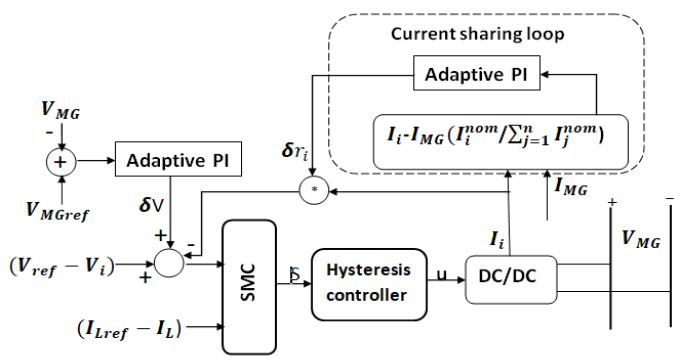

Fig. 6: Adaptive droop control method proposed in[11]

control is mentioned in [11] that consists of two PI controllers to perform droop for improving load sharing accuracy. The adaptive PI controller is utilized for shifting voltage reference by adjusting droop curve. A sliding mode control is used to replace the inner loops in conventional droop control method. Adaptive PI controller gains are defined as a function of error in current sharing so that the gains will be automatically adjusted according to change in load or line parameters. The adaptive droop method requires more parameters to be defines than normal PI control.

3. LIMITATIONS OF THE TRADITIONAL DROOP CONTROL METHOD IN DC MICROGRID

The first issue is the deterioration of power sharing accuracy. As the converter output voltages cannot be same due to the extra voltage drop via cable resistances. Secondly, the voltage regulation increases due to the droop action. The two flaws of the conventional droop control approach indicated above are discussed in detail as follows.

3.1. DC voltage deviation

Fig.7 represents a DC microgrid with two sources, where each converter is simplified by the Thevenin equivalent circuit.

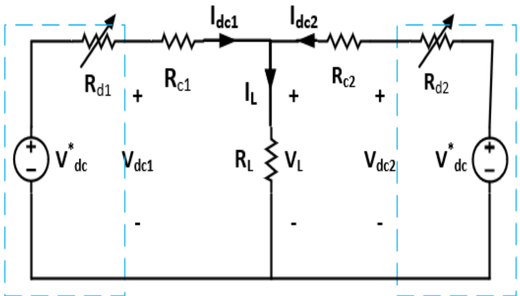

Fig. 7: Two sources operating in parallel in DC-MG

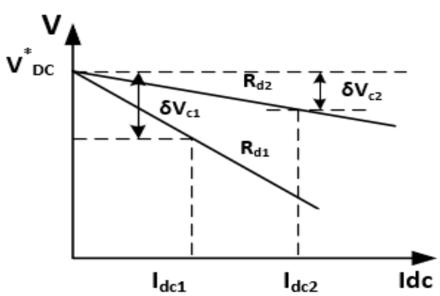

Fig. 8: Droop characteristics for unequal droop coefficients

The converter reference is expressed as

$$V_{dci} = V_{dc}^{*} - i_{dci}.R_{di} \tag{1}$$

where V_{dci} is output voltage value of converter and V_{dc}^{*} is the output voltage reference, i_{dci} is converter output current, R_{di} is the droop coefficient, i=1,2 for a two source system.
from (1) the deviation in voltage can be represented as

$$\delta V = i_{dci}.R_{di} \tag{2}$$

to restrict the voltage deviation within the permissible range, the value of the droop coefficient should be set as shown in Fig.8

$$R_{di} \leq \frac{V_{maxdrop}}{i_{dcfl}} \tag{3}$$

where $V_{maxdrop}, i_{dcfl}$ are maximum allowable voltage drop and full load rated current.

3.2. Current sharing deterioration

Thevenin equivalent resistance can be determined as the virtual resistance from (1). From the Fig.7. we can write as

$$V_L = V_{dc}^{*} - i_{dc1}(R_{d1} + R_{c1}) = V_{dc}^{*} - i_{dc2}(R_{d2} + R_{c2}) \tag{4}$$

When the converters reference and load voltages are equal then from (4) the expression for an n converter system can be written as

$$i_{dc1}(R_{d1} + R_{c1}) = i_{dc1}(R_{d2} + R_{c2}) = ... = i_{dcn}(R_{dn} + R_{cn}). \tag{5}$$

Current sharing can be represented as

$$\frac{i_{dc1}}{i_{dc2}} = \frac{R_{d2} + R_{c2}}{R_{d1} + R_{c1}} \tag{6}$$

According to (6), the accuracy of load current sharing is a factor of droop resistance and line resistance.

4. SECONDARY CONTROL METHODS

There are different control methods available to accomplish precise load power sharing while keeping voltage regulation to a minimum value across converters operating in parallel. To address the trade-off between voltage regulation and power sharing accuracy, secondary control layers were added which provides the reference for primary control layer and keeps the parameter to be controlled within acceptable range. Fig.9. represents the classification of secondary control methods based on the communication links available. Fig.10.

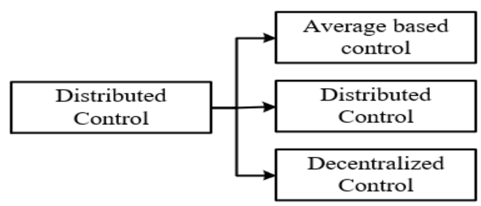

Fig. 9: Classification of secondary control methods

represents the shift in V_{ref} for same loading conditions. As shown in Fig.10. in primary control the operating point is away from the desired reference and it adversely affected to high loading conditions due to the presence of line resistances. After implementing secondary control, voltage reference is shifted such that the system always operates at its nominal values. In [12] to improve current sharing

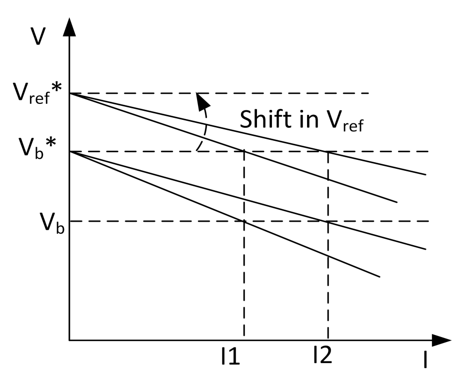

Fig. 10: Representation of shift in reference for same current sharing

accuracy and voltage regulation, two methods were implemented. In the first method, reference to the converter current is generated in terms of load and rated currents of converter. It is compared with the converter current so as to reduce the error in current sharing. In the second method, droop coefficients are generated by using heuristic search optimization and particle swarm optimization technique to find the optimal droop coefficient to reduce the current sharing error. However the proposed method provides both voltage regulation and current sharing accuracy relying on the values of bus voltage and load currents which are not possible to measure continuously.

From the communication point of view, secondary controllers were distinguished as centralized, decentralized and distributed.

4.1. Centralized control method

As represented in Fig.11. the centralized control scheme is used in DC-MG with a central controller connected to sources and local controllers through a high bandwidth communication network. A centralized controller is also termed as supervisory controller.

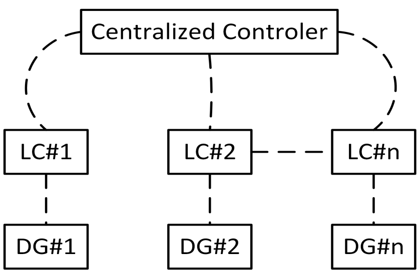

Fig. 11: Centralized control method

In [13], a basic master-slave DC-MG control system was established without a high bandwidth communication link. It was named as DC Bus Interacting (DBI) method, the method suggested can able to regulate the bus voltage even under the failure of communication link at a cost of convergence rate. In [14],[15] a multi-layer control method was proposed to avoid trade-off in voltage regulation and load sharing. In [16],[17] a three-level (HL1, HL2, HL3) hierarchical based control based method was implemented to improve system reliability and economic operation. In [18] a three layer (primary, secondary and tertiary) hierarchical control method was suggested to provide Energy Management System (EMS), it uses an MPC based non-linear controller and optimization techniques to provide reference to primary layer in terms of voltage signals. Though the method working based on peer-peer communication without requiring a central controller, the availability of non-liner control and optimization techniques makes the system complex. Reference [19] used a global tertiary controller that provides the voltage reference points to each microgrid based on loading data for proportional sharing of load among MGs. Though the centralized control methods are accurate in achieving the objectives such as voltage regulation and load sharing accuracy at faster convergence rate, it is prone to SPOF which makes it less reliable.

4.2. Distributed Secondary control

As there is no central controller in a distributed control structure, it is more reliable than the centralized control method. As shown in Fig.12, in distributed structure the converters local controller can exchange information (variable of interest) directly through Low Bandwidth Communication (LBC) lines. It contains the information of local variables and it can be inferred that the distributed control method has the following merits over the centralized method: improved modularity, robustness to Single Point Of Failure (SPOF) and it is flexible and scalable. Method suggested in [20] provides a distributed control strategy to reduce the current sharing error. In the proposed control method, an error estimator was used that estimates the current sharing error which is given to a controller and the controller output is used to modify the droop curve. However, the methodology focuses only on current sharing accuracy.

The distributed controls are grouped into two categories which are average voltage or current sharing and cooperative control method.

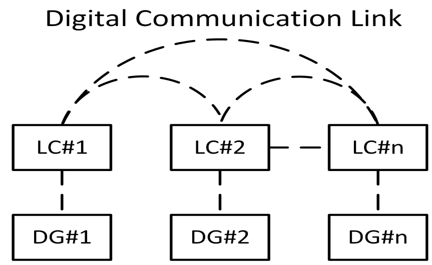

Fig. 12: Distributed control method

1) Average voltage/Current sharing method

In this method to avoid the trade-off in voltage deviation and load sharing error, the average voltage/current values of converters are used. Here the average values of voltage/currents are compared to the reference values and error is given to the controller to shift/change the slope of a droop curve. In [21],[22] average voltage and current controllers are utilized together to avoid the trade-off in voltage regulation and load sharing accuracy. In [23] linear active disturbance rejection control (LADRC) was used in the place of average voltage/current PI controller. The idea of LADRC in the proposed voltage/current controller is adding the total disturbance to the system and evaluating the performance of the controller to track and eliminate the total disturbance introduced. In LADRC the number of parameters to be tuned are more compared to conventional PI controller based system, and the results are almost similar to the case with PI controller. In [24] an average droop controller was used along with average voltage and current controllers and the droop gains are altered according to the loading conditions. This method (Fig.13) gives better performance under dynamic operating conditions but the convergence rate is slower and more number of PI controllers are used which may leads wind-up issues. In

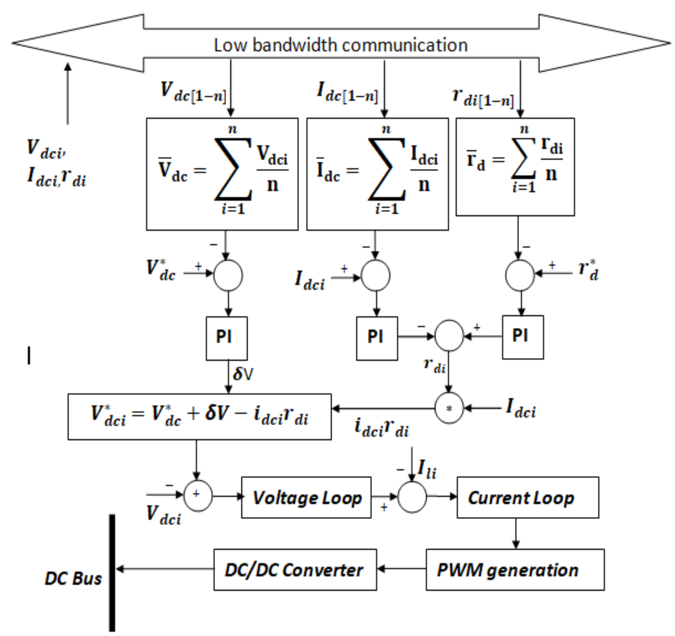

Fig. 13: Dynamic load current sharing control for DC-MG proposed in [24]

[25] a dynamic droop coefficient correction control (DCCC) is presented which corrects the droop coefficient automatically to achieve better power sharing. Voltage correction controller is used which compares the reference voltage with the bus voltage instead of average converter voltage. Though the method achieves proportional power sharing, measuring the bus voltage for control aspects is not feasible over long distance. A modified droop control algorithm

was proposed in [26] to maintain accurate current sharing and voltage regulation. The method adopted based on the percentage of current sharing for each module to the total load current under same line resistances. Maintaining same line resistance may not be possible which plays a key role in current sharing accuracy and voltage regulation. In [27] a virtual voltage based secondary controller was proposed to avoid the trade-off in voltage regulation and load sharing. Though the method tested under different ratings and different loading, it has to be tested for plug-play operation.

In [28] a quality index based search algorithm was introduced which is function of load sharing error and voltage drop. Quality index attains the optimum point of droop value iteratively to maintain minimum load current sharing error. Though the method results in accurate load sharing it requires significant amount of computational efforts. An effective approach for load power sharing is given in [29], but it requires faster communication lines to achieve precise load current sharing. In [30] a digital average current sharing was implemented in which average value of converter current was compared with each converter current, error was added to the droop controllers reference. This method proved effective for managing the bus voltage and load sharing, but the the shifting gain and droop gains need to be defined by the user. In [31] an adaptive droop control method was proposed that could eliminate circulating currents by maintaining proportional load current sharing based on average current and voltage drop. Also the method adopted need to be verified for the larger line resistances which can costs voltage deviation. In [32] droop gains are obtained by the droop index, which is the function of power loss and current sharing difference. Despite the fact that the approach results in more precise load sharing, it requires a significant amount of processing effort. Reference [33] proposed a secondary controller consisting of voltage mode and current mode and the mode of operation depends on the required condition. A secondary controller to maintain proportional power sharing was proposed in [34]. In this method precise load current sharing and minimum voltage deviation was attained by means of adding a proportional gain to reference voltage under both resistive and Constant Power Loads (CPL). The proposed method verified under tie line operation where two microgrids are connected through a tie line to share power according to the requirement. As

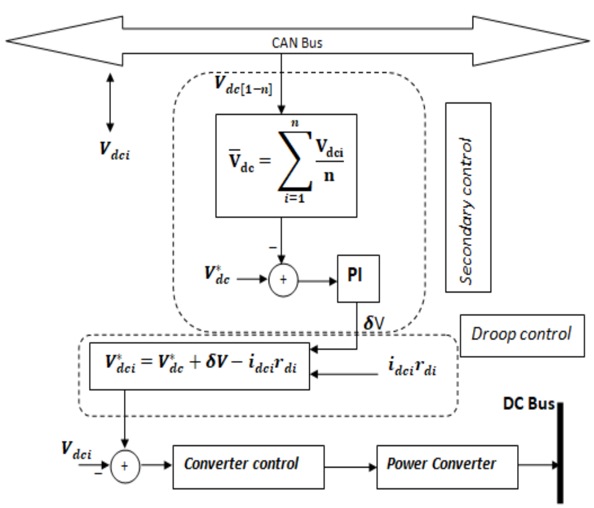

Fig. 14: Voltage correction factor based control structure proposed in [35]

shown in Fig.14. an average voltage regulation method consisting of an algorithm for voltage correction factor is implemented in [35] to improve load sharing accuracy and voltage regulation. Though the method implemented was providing accurate load sharing at small line impedance where the voltage drop is considerably small. It has to be tested for larger line impedance for effectiveness.

References [36] and [37] used an average power based controller and a voltage controller which is function of average power. The proposed method achieves both power sharing and voltage regulation and it is tested for various communication delays, failure of communication channel and plug and play conditions. It reduces communication stress by exchanging only one variable via low bandwidth communication link, but the method proposed in [37] was not rapid in response. The method proposed in [38] used a voltage controller in addition to the average power controller to achieve both power sharing accuracy and voltage regulation at a cost of convergence rate. In [39] a fuzzy controller was used instead of PI controller in the second layer for achieving both the power sharing accuracy and voltage regulation. However the method achieves accurate power sharing, it has to be tested for dynamic operating conditions for effectiveness.

2) Cooperative control method

The Consensus theory or Synchronization drives cooperative control. The objective is to assist controller to drive all nodes to have same steady state constant value (Consensus value). Consensus protocols are implemented to improve the speed of convergence and system stability. Consensus protocols relies on the system (process) dynamic model. In Fig.15. the observer at node i gets its neighbors

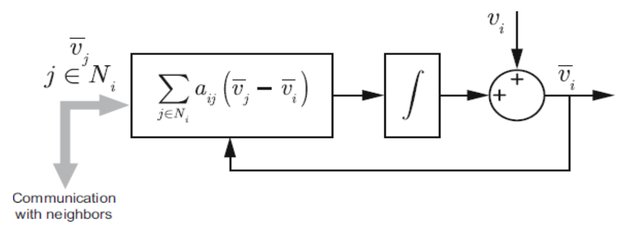

Fig. 15: Dynamic consensus protocol [40]

estimate, $\tilde{v}_j$ then by processing neighbors estimate and local voltage measurement v_i, the observer updates its own estimate $\tilde{v}_i$. This updating protocol is termed as dynamic consensus protocol. This protocol is basically used for global averaging as well as node averaging. An ideal current sharing secondary controller with low communication was proposed in [41]. As shown in Fig.16, the controller determines the global value of ideal current to be provided by each source using the consensus protocol based on the initial estimate of rated source current and the average estimate of adjacent source currents. To enhance voltage regulation, the average estimate

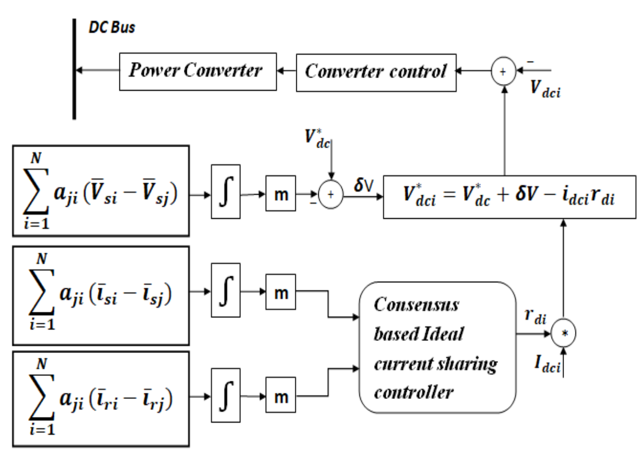

Fig. 16: Ideal current sharing controller for DC microgrid proposed in [41]

of source voltage shifts the droop characteristics and the global estimation of ideal current makes the proportional current sharing. Hence the trade-off in voltage regulation and power sharing can be achieved simultaneously. There are different types of consensus protocols based on application such as second-order consensus [42] and event-triggered consensus [43], [44]. In event triggering method the control inputs are generated on the occurrence of events. When the plant states (bus voltage or converter currents) deviates a certain threshold from the desired value (error band) it is considered as an event. It is similar to time triggering but event triggering can reduce communication stress, power consumption and burden on processor by taking samples based on the event generated.

A new event-triggered distributed secondary control strategy for single-bus DC microgrid was proposed in [45], and it was able to achieve accurate current sharing and voltage regulation at same values of line resistances. This has to be verified under different line impedance for effectiveness. In [46] a distributed event-triggered H_∞ consensus algorithm was proposed to achieve accurate current sharing. This algorithm provides the proportional load sharing at a cost of voltage regulation. In [47] a new distributed secondary control strategy with event-triggered signal transmissions was proposed. However, this method fails to work if the DC bus voltage is not available to converters. In addition, only resistive load is considered. Finite-time consensus as implemented in [48] allows for convergence in a finite number of steps, while eliminating disturbances and dealing with uncertainties it may introduce chattering in response. Fixed time consensus is used in [49]. As compared to finite time and event triggered method, fixed time is having better convergence and scalability.

Secondary control methods based on consensus can achieve voltage shifting term and current sharing correction term with the use of reduced communication links. A network with reduced communication links may take more time to converge and time of convergence can be reduced with the fully communicated system. So there always exists a trade-off in number of communication links and speed of convergence.

3) *Decentralized secondary control method*

In this approach the control methods are accomplished absolutely with local controllers without a Digital Communication Link (DCL). Decentralized methods are characterized into three classes: DC Bus Signaling (DBS), Power line signaling (PLS) and Adaptive droop calculation method. Among all DBS is popular in which DC bus is used as information carrier [50]. The control between renewable energy sources, energy storage system, loads and converters are carried out based on difference in DC bus voltage levels. Since the communication between source controllers occurs through the DC bus instead of an external communication link, the sources can be effectively controlled using terminal quantities as in decentralized control. Though DBS enables a distributed control method to be applied with the same stability benefits as decentralized control, this control method is less complex and no communication required. The presence of errors in estimation of DC bus voltage makes it inaccurate and also it has performance issues due to the unavailability of information from other components. The other method is PLS which is normally injecting sinusoidal signals of specific frequency to DC bus that allows each device to send and receive data [51]. Adaptive droop calculation is widely used in ESS to balance SoC (State of Charge) to avoid over-charging or discharging.

Table.1 provides the comparison of different secondary control methods based on the information exchanged and property of the controller (voltage correction, droop coefficient correction) along with the nature of the control strategy existing in DC microgrids. From the comparative analysis we can understand that the distributed control methods uses lower communication compared to centralized control, effective in achieving the objectives such as power sharing accuracy and voltage regulation at faster convergence rate with minimum number of variable exchanges over communication lines at reduced complexity.

The summary of decentralized, centralized and distributed control strategies are given in Table.2.

- Although the traditional droop control approach is reliable as a primary control, it cannot avoid the trade-off between power sharing and voltage regulation which means it either can achieve voltage regulation or proportional power sharing but not both.
- In spite of the fact that secondary control methods perform better in terms of power sharing and voltage regulation, its performance is effected by the availability of communication links (among the local converters for exchanging information) and delays. Based on the availability of communication links it is divided into three categories :centralized, decentralized and distributed control methods.
- Centralized method uses a central controller to provide the corresponding commands through dedicated High Bandwidth Communication channels (HBC) according to the desired objective. Although the central controller has the most versatility in terms of attaining the best results, it has a single point of failure (SPOF) which makes it less modular.
- Due to the absence of communication the decentralized method provides high reliable operation (Droop control method) but the absence of global information makes it less flexible in operation.
- Distributed control methods are becoming more popular because of the modularity and great reduction in communication stress by choosing variable of interest in low band-width communication lines which can eliminate SPOF effect on the system.

5. CONCLUSION

In this paper, a review of existing secondary control methods for achieving multiple objectives such as power sharing accuracy, proportional load sharing at minimum voltage regulation and circulating currents at a faster convergence rate was discussed. The local control used for the converter plays a crucial role not only in achieving proper load sharing or voltage regulation but also in achieving coordinated operation when the secondary and tertiary layers are subjected. Though the local control (droop) is reliable and efficient, it suffers the trade-off in voltage regulation and current sharing accuracy. To avoid the trade-off, secondary control layers were introduced to the control structure. The secondary control methods are classified based on the communication links available such as centralized, decentralized, distributed control. Distributed control methods are structurally similar to decentralized control except for the digital communication links, but can achieve similar functions as centralized methods. The digital communication links make distributed control more flexible than decentralized control under dynamic operating conditions. The distributed control avoids the SPOF as there is no central controller, which makes it more reliable compared to centralized control methods. To summarize, each listed secondary control method has its own set of traits, benefits, and drawbacks. The study of distributed control and load stability has advanced in recent years.

To make distributed control more effective for secondary and tertiary control layers, complex mathematical analysis is required which is challenging. Also, the distributed control strategies need to be further evolved as simpler which can eliminate the computational burden and mathematical complexity, it has to maintain rapid convergence rate without compromising stability under various loading conditions such as constant current, constant impedance, and constant power loads (non-linear loading). It also needs to provide stable operation under load disturbances, source uncertainties, at different communication delays and communication failure. It can be made possible with the combination of linear and non-linear control algorithms (sliding mode, back stepping algorithm, model predictive control) which can be considered as hybrid control methods, and it will be more effective by adding the optimization techniques. Adaptive control techniques need to be used to mitigate the adverse dynamic effects imposed by Constant Power Loads (CPLs) which make the system unstable because of its negative incremental characteristics. Furthermore, it is advised to investigate the effects of various CPLs on system performance.

Table. 1: Comparison of secondary control methods in DC microgrids

Methodology implemented	Shared information among converters	Power/current sharing correction	Communication among converters	Voltage restoration
Average current based [30]	Current	Voltage shifting	Neighbors	Distributed
Average voltage and current [22]	Voltage, current	Voltage shifting	All	Distributed
Average voltage, current, droop [24]	Voltage, droop coefficient,current	Voltage shifting and droop adjustment	All	Distributed
Average current [29]	Current	Voltage shifting and droop adjustment	Neighbors	Distributed
Average current [31]	Current	Voltage shifting	All	None
Average voltage [36]	Voltage	Voltage shifting	Neighbors	Distributed
Average Power [37]	Power	Droop adjustment	Neighbors	Decentralized
Average consensus based [42]	Voltage, current	Voltage shifting and droop adjustment	Neighbors	Distributed

Table. 2: Summary of control methods in DC microgrids

Control strategy		Load sharing and voltage regulation	Features	Advantages
Decentralized control	DBS	Good	Less immune to load changes	Less complex and more reliable
	PLS	Better	Communication is a bit slow	
Distributed control	Average Based	Good	More reliable but not much scalable	Immune to single point of failure. Lower communication stress and modular in nature
	Cooperative Consensus	Excellent	More reliable and scalable but lot of analytical complexity is more and chances of estimation based errors in the system	
Centralized control		Excellent	Subjected to SPOF	Best in results due to proper coordination and availability of global information.

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