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Centralized Control for DC Microgrid Using Finite State Machine

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Abstract—In this paper, an autonomous communication-based centralized control for DC microgrids (MG) has been developed and implemented. The proposed controller enables smooth transition between various operating modes. Finite state machine (FSM) has been used to mathematically describe the various operating modes (states), and events that may lead to mode changes (transitions). Therefore, the developed centralized controller aims at optimizing the performance of MG during all possible operational scenarios, while maintaining its reliability and stability. Results of selected cases have been presented. These results show stable transition between modes, verifying the validity and applicability of the proposed controller.

Index Terms—Centralized control, communication based control, DC microgrid, finite state machine, smart grid, state flow.

I. INTRODUCTION

Smart grids are dynamically interactive real-time power grids, which have been introduced to address the urgent need for increased resilience, flexibility and self-healing capability. Smart grids are enabled by several emerging technologies, e.g. information and communication technology (ICT), advanced metering infrastructure (AMI), microgrids and electrical vehicles. Essentially, they involve integration of measuring circuits, sensors and communication networks, among various technologies, which are collectively capable of supervising the electric grid and managing the energy flow in real time [1]-[3]. Microgrid is one of the main pillars of smart grids, which prominently contribute to its level of resiliency since it could seamlessly indemnify for partial grid generation loss [4]-[6].

Microgrid is a local distribution network comprising distributed energy resources (DER), energy storage systems (ESS) and loads, which aggregately function in a controlled fashion as a single entity, in either a grid-tied mode or an islanded mode [7]-[8]. Each of the MG components is controlled via a dedicated local controller. Local controllers must be coordinated to maintain load/generation balance, and optimize the performance of a MG. Coordination can be achieved through one of the following three architectures.

Communication-less control: where there are no communication links between local controllers, and the deviation in the DC bus voltage is used to signal load/generation unbalances [9]-[10]. Therefore, it is also known as voltage droop control. This architecture has an advantage of being relatively reliable since it does not depend on communication systems and their inherent drawbacks (e.g. delays and packet loss). However, some of the main drawbacks of this architecture are suboptimal microgrid operation, and circulating currents.

Distributed communication-based control: where communication links exist between the local controllers (LCs). LCs coordinate their decision, but final control decisions are being processed and executed locally. This architecture, if

properly designed, is immune to single point failure, i.e. MG can maintain full operation even with the failure of some of the LCs or communication links. However, it introduces complexity, and cannot achieve optimal MG operation [11].

Centralized communication-based control: where event/command signals between the LCs and a supervisory centralized controller, are being transmitted/received directly. Since the supervisory controller has global information on the various MG components, a predesigned algorithm can be implemented to achieve any desired objective, e.g. optimal operation. However, the reliability of this architecture is dependent on that of the communication system being utilized [11].

Development of an automated control system, which preserves MG stability/reliability during all possible scenarios while maintaining optimal operation is badly needed. Therefore, this challenge has attracted the attention of many researchers globally. However, the research that has been performed to address this challenge either focused on a specific case [12], or did not consider all possible scenarios/modes of operations. Moreover, it was mostly focused on designing a controller that guarantees stable MG operation [13]-[17], overlooking some other essential performance features including: energy/economic savings during grid connection, mitigating renewable energy intermittency, etc.

In this paper, an autonomous centralized control, will be developed for DC MG, and implemented using finite state machine (FSM). The controller includes a forethought control logic implemented within, to guarantee MG reliability and resiliency during various modes of operation.

II. MODEL ARCHITECTURE

The DC microgrid considered in this paper comprises the following: a 1.5 kW battery system integrated to a 300V common DC bus through a bidirectional DC-DC charger; a 4 kW peak photovoltaic (PV) system that is connected to the DC bus through a DC-DC boost converter; a 6 kW controlled DC load that is connected to the DC bus; an AC-DC bidirectional smart inverter tying the main grid to the common DC bus. As illustrated in Fig. 1, a microgrid Central Controller (MGCC) is used to manage and control the microgrid.

The various individual converters are controlled locally through their LCs. Monitoring the AC and DC buses is being achieved by an AC agent and a DC one, respectively. The AC agent is used to detect any voltage/frequency deviations according to IEEE standards [18]. The DC agent monitors the DC bus voltage deviation [19]. The LCs, AC and DC agents, along with the solid state relays (SSRs) from the protection system, all report their statuses/events to the MGCC. The MGCC processes all inputs through a predesigned logic yielding the proper mode/action to be performed, to optimally achieve stability and reliability.

Fig. 1. Microgrid architecture

The control scheme for DC MG is hierarchical and communication based. In the primary layer, the local controllers are state driven (i.e. controlling their respective converters by continuously monitoring certain state variables), which requires incessant communication, e.g. voltage/current measurements and pulse signals to the switches of the converters.

In the secondary layer, the modes and set points are being assigned to each LC by the MGCC, to maintain the required voltage level within the DC MG and optimize its operation. The MGCC is event driven, i.e. it does not require continuous communication with the LCs. The devised logic within the MGCC was conceived such that the MGCC only takes an action if new event occurs, which reduces the communication requirement within the secondary layer, e.g. the required bandwidth. The tertiary controller handles the functionalities that exceed the boundaries of a single microgrid, e.g. utility control of a group of microgrids. The main focus of this paper is the secondary layer.

III. SECONDARY CONTROL USING FINITE STATE MACHINE

Finite state machine (FSM) provides a mathematical means to represent a finite number of states, and describe the transition between them. To represent the proposed control scheme, FSM has been used. FSM can be thought of as a machine with a finite number of operational conditions called states, or in this case, “modes.” The machine can be in only one state at any given time, and can transition to other states based on events.

The FSM for the entire DC MG control could be represented by the following variables (Σ , M , m_{00} , δ), where:

Σ : is a finite set of inputs to the MGCC, which are the events in Table 1.

M : is a finite, non-empty set of modes, which comprises all modes sets:

- M_{00} (Grid-tied/Energy saving mode) = $\{m_{00}, m_{01}, m_{02}\}$, such that $\forall m_{0j} (m_{0j} \in M_{00} \rightarrow m_{0j} \in M)$ where $j = 0, 1, 2$.
- M_{10} (Islanding mode) = $\{m_{10}, m_{11}, m_{12}, m_{13}\}$, such that $\forall m_{1j} (m_{1j} \in M_{10} \rightarrow m_{1j} \in M)$ where $j = 0, 1, 2, 3$.
- M_{20} (Utility mode) = $\{m_{20}\}$, such that $m_{20} \in M$.

- M_{30} (Shutdown mode) = $\{m_{30}\}$, such that $m_{30} \in M$.

Therefore $M = \{M_{00}, M_{01}, M_{03}, M_{04}\}$, which will be more explicitly explained in section V.

m_{00} : is the initial mode of the FSM, $m_{00} \in M$.

δ : is the mode transition function; $\delta: M \times \Sigma \rightarrow M$, it can be seen in the transition Table 1.

The control action of the LCs is dependent upon the mode/sub-mode of operation being triggered by the MGCC, e.g. during m_{00} (grid-tied sub-mode), C_{B0} (boost converter LC) is MPPT controlled, while during m_{13} , it is voltage controlled. The modes are based on the event signals being transmitted to the MGCC, and the logic/algorithm implemented within, which will trigger a proper transition. Transitions will be discussed further in section IV.

The levels of load shedding are designed to be dynamic within the islanding mode. The logic was prepared to have downstream load shedding during M_{10} , i.e. no reconnection of loads happens unless normal operation is retained, to preserve the safety of the loads. The levels of load shedding are selected based on the emergency loads, available resources at the instant of load shedding, and a margin of safety to account for solar intermittency. An average constant load within the time interval of the load shedding process was assumed. Four levels of load shedding were used within the islanding mode: (1) the first level of load shedding that is triggered at the moment of islanding. This level is a function of the available resources; (2) the second level of load shedding takes place when the batteries are depleted; it is related to the battery and solar systems sizes, and the percentage of current that will be assigned to the batteries to charge with, e.g. less than 50% of I_{lc} (rated current at 1C rate of charge). The percentage of the I_{lc} depends on the amount of the emergency loads and their priority; (3) the third level occurs when the boost converter is tripped or its sunset, and is a function of the battery size; and (4) the last level of load shedding is triggered when the bidirectional converter is tripped while the boost converter is still available. At this level of load shedding, it is preferable to keep a minimal portion of the total load, and only keep the loads that are less sensitive to voltage variations, in case of intermittency. However, if voltage variations are significant, transition to M_{30} will occur to preserve load safety.

IV. OPERATIONAL MODES LAYERS AND TRANSITION CONDITIONS

The architecture of the control scheme starts with the main layer that encompasses four modes: (1) grid-tied (energy saving) mode, which is the initial mode M_{00} ; (2) islanded mode M_{01} ; (3) utility mode M_{03} ; and (4) shutdown mode M_{04} . M_{00} is assumed to be the initial mode of the entire FSM. It aims at achieving economic operation.

A. Main layer

Within this layer, several transitions may occur. For instance, if a grid outage takes place and gets reported by SSR_{PCC} ($S_3 = 0$), or the AC agent signals AC voltage/frequency exceeding permissible limits and lasting beyond the average clearing time specified in [36] to the MGCC ($S_1 = 0$), a transition to M_{10} will happen. However, in case the utility sends a signal to take control of the MG ($S_6 = 1$), if all MG resources are available, a transition to M_{20} will occur, and if

all resources are not available at any given instant, a transition to M_{30} will happen. Other transitions may happen depending on the events being triggered, which are summarized in Table. 1 and Fig. 2.

B. Grid-tie/Energy saving Mode

Transitions within that mode are triggered by S_7 , S_5 and/or S_8 , e.g. starting with m_{00} , the MGCC commands the inverter to maintain the DC bus voltage, C_{B0} to operate as MPPT and the bidirectional converter LC (C_{Bi}) to be idle, i.e. current control with $I_{ref} = 0$. If the utility signals the MGCC that the energy price is low ($S_7 = 1$), the MGCC checks the last status of C_{Bi} to confirm that the battery is not full ($S_8 = 0$), and the SSR_{Bi} to assure no fault operation ($S_5 = 1$), a transition to m_{01} takes place. In m_{01} , the bidirectional starts charging the battery system with I_{lc} to exploit the advantage of low energy price, while the inverter and the boost converter are still maintaining the same operation from m_{00} . However, if the energy price is high ($S_7 = 0$), the SSR_{Bi} last report was no fault operation ($S_5 = 1$), and the C_{Bi} last signal that the battery has the capability to discharge ($S_8 = 1$), a transition to m_{02} happens. In m_{02} , the LCs maintain the same tasks of m_{00} , except for the bidirectional converter, starts discharging with the maximum current I_{lc} . The rest of transitions can be observed from Fig. 2 and Table. 1.

C. Islanding Mode

M_{10} is triggered when SSR_{PCC} signals the circuit breaker to open and informs the MGCC with that event ($S_3 = 0$), e.g. due to a power outage. M_{10} includes four sub-modes, islanding m_{10} , contingency m_{11} , critical m_{12} , and extreme m_{13} sub-mode. A number of transitions may possibly takes place, one at a time. For example, starting from sub-mode m_{10} , shown in Fig. 2, the MGCC trigger the first level of load shedding, C_{B0} to operate as MPPT, and C_{Bi} to fix the DC bus voltage. If the SSR_{Bi} detects a fault where it is located, e.g. due to abnormal operation of the bidirectional converter or a fault, and report it ($S_5 = 0$), a transition to m_{13} will happen. In m_{13} , C_{B0} maintains the DC bus voltage, and a maximum level of load shedding will be triggered. At this level, the load almost equals ~10-20% of the solar peak power that was available within the previous hour. The type of loads connected during that level of load shedding should be able to handle a wide range of voltage variation, since the battery is not available to buffer the expected power fluctuations. If the DC voltage changes beyond the permissible limits of [36] during m_{13} ($S_2 = 0$), a transition to m_{13} will take place to protect the loads as shown in Fig. 2. However, starting from m_{10} , if C_{Bi} informs that the batteries are depleted ($S_8 = 0$), while the boost converter is still available, through checking the last status signal from the SSR_{B0} by the MGCC ($S_4 = 1$), a transition T_{11} to m_{11} will occur. In this case, the second level of load shedding will take place, such that a portion of the available solar energy is used to charge the batteries with a maximum of half I_{lc} , to guarantee continuous operation of the loads for as long as possible. The rest of energy is used to maintain supplying the remaining loads. This happens while the boost converter is MPPT controlled, and the bidirectional converter is still maintaining the DC bus voltage. On the other hand, also starting from m_{10} , if solar intermittency occurred while the bidirectional converter is maintaining the DC bus voltage, the battery system might over discharge to keep supplying the

loads. If this takes place for a time interval that is greater than the settling time of the nested PI of the bidirectional converter LC ($S_9 = 1$), or the SSR_{B0} signals that the boost convert is tripped ($S_4 = 0$), then a transition T_{17} to m_{12} will take place. The reason for adding the settling time of the converter PI to the transition condition, is to guarantee that the transient oscillations of the bidirectional converter LC does not lead to false transitions. The controller oscillations may happen when the converter is trying to maintain the DC bus voltage. A condition to prevent over discharge was added, to extend the battery system availability during this mode. The rest of the transitions could be observed from Fig. 2, and Table. 1.

D. Utility and shutdown Modes

The goal of the utility mode M_{20} , is for the utility to take control over the MG, according to a predefined agreement, e.g. to aggregate multiple MGs for virtual power plant operation, or enhance the voltage level by injecting reactive power. In this case, the inverter LC is performing current or P/Q control. As for the shutdown mode M_{30} , its objective is to guarantee a shutdown in case all the resources are tripped or not available at any given moment, or in case the permissible limits of the DC voltage are violated during m_{13} , in order not to jeopardize the loads safety.

V. RESULTS AND DISCUSSIONS

In order to illustrate the operation of the proposed secondary communication-based FSM-enabled controller, some selected scenarios will be presented and discussed. Each case is presented by a set of four subplots. Each subplot has five sections, each section reflects a new event or a set of events taking place. The (a) subplot of each figure represents DC currents for the inverter, boost converter, bidirectional converter and DC load. Subplots (b), (c) and (d), demonstrate the DC bus voltage, AC current from the inverter to the grid, and AC voltage, respectively.

A. Case One

This case shows the operation of the MGCC to control the DC MG in case of islanding, showing solar intermittency impact on the transition between modes of operation among other events. Section (1) displays the transition T_{11} from m_{00} to m_{10} , due to a blackout being signaled by SSR_{PCC} ($S_3 = 0$). The first level of load shedding is triggered by the MGCC, reducing DC load current and dropping the AC current from the MG to the grid to zero as shown in Figs. 3(a) and 3(c), respectively. During m_{10} , the MGCC commands C_{Bi} to maintain the DC bus voltage to 300 V, and C_{B0} to maintain MPPT control, which can be noticed in Fig. 3(a). Throughout section (2), solar intermittency caused the batteries to over discharge beyond 5 A, for a period of time longer than the settling time of C_{Bi} PI (200 msec). Consequently, S_8 becomes one, signaled by C_{Bi} . Therefore, the MGCC checks the last status of SSR_{Bi} , if there is no fault ($S_5 = 1$), a transition T_{12} to m_{12} happens. In m_{12} , another level of DC load shedding is introduced, which can be seen from the DC load current in Fig 3(a). The LCs maintain the same duties as in m_{10} . During m_{12} , the LCs maintain the same duties as in m_{10} . During section (3), the boost converter is tripped, and in section (4), it is reconnected. Concurrently, C_{Bi} reacts to maintain the DC bus voltage (i.e. discharging when the boost converter was tripped, and charging when it was reconnected). Section (5) represents

Table 1. Transitions among various modes/sub-modes of DC MG

	Transition	Transition condition	Transition Description	4
Main Mode Transitions	T_1	$S_3 = 0$	Tripping of the Inverter triggered M_{01} , bidirectional converter fixing DC bus voltage and boost converter operating at MPPT while the first level of load shedding is triggered	
	T_2	$S_3 = 1 \ \&\& \ S_1 = 1$	Synchronization conditions are set for reconnection the DC MG to the grid	
	T_3	$S_3 = 0 \ \&\& \ S_5 = 0 \ \&\& \ S_4 = 0$	Tripping of the Inverter, Boost and Bi-directional converter will cause the MG to shut down	
	T_4	$S_6 = 0$	Utility control over the MG is disabled thus the operation is restored to grid tie mode	
	T_5	$S_6 = 1 \ \&\& \ S_3 = 1 \ \&\& \ S_5 = 1 \ \&\& \ S_4 = 1$	After confirming that all resources are operational the utility is granted control over the MG	
	T_6	$S_3 = 0 \ \&\& \ S_5 = 0 \ \&\& \ S_4 = 0$	Tripping of the Inverter, Boost and Bi-directional will cause the MG to shut down	
	T_7	$S_5 = 0 \ \&\& (S_4 = 0 \parallel (S_2 = 0 \ \&\& \text{after } (t_s)))$	Tripping of the Boost and bidirectional converter, or the DC bus voltage deviated beyond the limits, t_s is added to guarantee unnecessary transition due to disturbance during settling time (t_s) of the PI	
Grid tie Mode Transitions	T_{01}	$S_8 = 1 \parallel S_5 = 0$	Batteries are full charged or bidirectional converter is tripped	
	T_{02}	$S_7 = 1 \ \&\& \ S_8 = 0 \ \&\& \ S_5 = 1$	Energy price is low, batteries are not fully charged, and the SSR_{Bi} reports no fault	
	T_{03}	$S_7 = 0 \ \&\& \ S_8 = 1 \ \&\& \ S_5 = 1$	Energy price is High, Batteries are not depleted, and the SSR_{Bi} reports no fault	
	T_{04}	$S_8 = 0 \parallel S_5 = 0$	Batteries are depleted or bidirectional converter is tripped	
Emergency Mode Transitions	T_{11}	$S_8 = 0 \ \&\& \ S_4 = 1$	Batteries are depleted and boost converter is available	
	T_{12}	$(S_4 = 0 \ \&\& \ S_5 = 1) \parallel (S_2 = 0 \ \&\& \text{after } (t_s))$	Boost converter is tripped and bidirectional converter is available, or DC bus voltage deviated severely	
	T_{13}	$S_5 = 0$	Bidirectional converter is tripped	
	T_{14}	$(S_4 = 1 \ \&\& \ S_5 = 0) \parallel S_8 = 0$	Bidirectional converter is tripped and the boost converter is available, or batteries are depleted	
	T_{15}	$S_5 = 1$	Bidirectional converter is reconnected	
	T_{16}	$S_5 = 0$	Bidirectional converter is tripped	
	T_{17}	$(S_4 = 0 \ \&\& \ S_5 = 1) \parallel (S_9 = 1 \ \&\& \text{after } (t_s))$	Boost converter is tripped and bidirectional converter is available, or batteries over discharge

Fig. 2. Operational modes/ sub-modes of DC MG.

the tripping of the bidirectional converter, where the bidirectional output current drops to zero, triggering m_{14} . Within m_{14} maximum load shedding is triggered, C_{B0} is commanded to switch to voltage control, where the DC load current drops to $\sim 10\text{-}20\%$ of solar energy, and becomes equal the boost converter current, which can be noticed in Fig. 3(a). It can be observed from Fig. 3(b), the DC bus voltage during all events was maintained within the acceptable limits, by using the suggested FSM logic to maneuver various critical situations.

B. Case Two

This case shows the operation of the MGCC, during the grid-tied/energy saving mode M_{00} . Throughout section (1), a signal sent by the utility to the MGCC, informing it that the energy price is low ($S_7 = 1$). The MGCC checks the last SOC of the battery system through the latest signal received from the C_{Bi} , confirming it is not full ($S_8 = 0$). It also checks the last status of SSR_{Bi} assuring normal operation ($S_5 = 1$), which leads the MGCC to trigger T_{02} to m_{01} . Each converter LC maintains their ongoing tasks; the inverter maintains the DC bus voltage to 300 V, and C_{B0} operates as MPPT. C_{Bi} initiates

maximum charging ($I_{ref} = I_{1c}$), using current control as can be noticed in Fig. 4-a, where the bidirectional converter current becomes -5 A, i.e. charging with 5 A. Therefore, the inverter DC current increases to 5 A to maintain the dc bus voltage to 300 V as shown in Fig. 4(b). The AC current increases as well from the grid to the inverter, as shown in Fig. 4(c). For the interval of section (2), C_{Bi} signals that the battery system is fully charged ($S_8 = 1$), then m_{00} is retained by the MGCC through T_{01} , as shown in Fig 4(a), where the bidirectional converter output current drops to zero. The current of the inverter drops to zero as well. Therefore, the DC bus voltage is regulated as shown in Fig 4(b), since the DC MG can self-sustain its DC loads at that interval. During section (3), while m_{00} is still active, some solar power fluctuations start causing the boost converter output current to decrease gradually. The inverter DC/AC current increases in order to maintain the DC bus voltage, which can be noticed in Figs. 4(a), 4(b) and 4(c), respectively. During section (4), the irradiance goes back to its value of section (1), and the boost converter output current as well. This results in dropping the inverter DC/AC current to almost zero, maintaining the DC bus voltage, as shown in Figs. 4(a), 4(b) and 4(c), respectively. During the last segment, the utility signals high energy price to the MGCC ($S_7 = 0$). The MGCC confirms the availability of the bidirectional converter, by checking the last status report it got from the SSR_{Bi} . If there was no fault ($S_5 = 1$), a transition T_{03} from m_{00} to m_{02} takes place. C_{Bi} switches to current control and starts discharging at the rated current (I_{1c}) with 5 A. Therefore, the inverter DC current drops to -5 A to maintain the DC bus voltage to 300 V, i.e. sending 5 A to the grid, as shown in Figs. 4(a) and 4(b), respectively.

VI. CONCLUSION

An autonomous communication-based centralized controller for DC microgrid was developed in this paper. Various scenarios including severe conditions were accounted for during the design of the controller. FSM was used to realize the proposed controller. The proposed control scheme includes event-driven MGCC supervising a set of state variables-driven LCs. The controller aims at achieving a reliable and resilient operation while maintaining optimal performance. The hybrid state/event driven approach reduces the communication requirements. Several case studies have been presented. Results show the applicability of the proposed controller.

Fig. 3. Case one, showing operation during grid-tie mode.

Fig. 4. Case two, showing operation during islanding mode.

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