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Impact of Clustering Microgrids on Their Stability and Resilience during Blackouts

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***Abstract*—In this paper, the impact of clustering multiple microgrids during blackouts, on their stability and supply availability, will be investigated. Microgrids have the capability of satisfying their emergency loads during blackouts. However, distributed energy resources (DERs)-dominated microgrids are affected by the uncertainty of their input energy supply, e.g. impact of solar irradiance on photovoltaic (PV) output. Moreover, an individual islanded microgrid is prone to instability issues due to large sudden load/generation changes. In order to increase the supply security, and enhance system stability, we propose to use the existing distribution grid infrastructure, if applicable, during blackouts to form microgrid clusters. The paper discusses the required control hierarchy required to manage the microgrid clusters, and communicate with the Distribution Network Operator (DNO). A case study based on the 13-bus standard distribution feeder, and two microgrid models, is presented. Results show that microgrids clustering helps improve their performance and that the microgrid generator inertia has a direct impact on the stability of the microgrid cluster.**

***Keywords*—blackout; hierarchical control; inertia; microgrids (MGs); Microgrid cluster; smart grid; stability**

I. INTRODUCTION

Electric power systems are undergoing profound changes due to the ever-increasing need for a more resilient grid. Whereas, high reliability has always been the target of power system planners/operators, the recent wave of severe storms, which cause widespread power outages and significant economic losses, revealed the fact that the existing power system are not resilient enough against natural disasters. Power systems are not only vulnerable to natural disasters but also to any other destructive events, such as humane errors, cyber attacks, etc. According to a recent Wall Street Journal report, an attack on only 9 substations could cause a massive blackout [1].

Massive blackouts have been reoccurring almost yearly for the past two decades worldwide. During the first half of 2015, four major blackouts occurred. One of those blackouts was caused by a terrorist attack, and left 80% of Pakistan without power. Another blackout was due to operational problems, and disconnected over 90% of Turkey, i.e. impacted about 70 million people.

Smart grids are smart and flexible power grids that have emerged with the introduction of new technologies and features, e.g. increased dependency on ICT, high renewable energy penetration, Advanced Metering Infrastructure (AMI), microgrids (MG), electric vehicles, etc. Microgrid is one of the key applications of smart grids that significantly contribute to the level of resiliency of the smart grid.

A microgrid is a smaller, more localized version of the main power grid, which brings distributed energy resources (e.g. wind, solar, natural gas) closer to where the energy is being used within clear electrical boundaries, improving the overall efficiency of the power system. Moreover, the microgrid has its own controller, and has the capability to operate while connected to the grid, in a so-called grid-connected mode, or disconnected from the main grid when needed, in an islanded mode.

The independent microgrid controller monitors the status of the point of common coupling (PCC), where the main grid and microgrid connect, and isolate the microgrid when a power disturbance occurs, e.g. due to a fault, in the main grid. Typically, during blackouts, individual islanded microgrids are operated independently from each other. If the generation of these microgrids is dominated by distributed energy resources (DERs), which are volatile and nondispatchable by nature, the stability of the islanded microgrids may be easily jeopardized by sudden changes in the load or generation. Connecting multiple microgrids, as shown in Fig. 1 during a blackout is possible with special switching on the distribution feeders, especially that the distribution infrastructures are typically underground and therefore they are intrinsically less susceptible to damage than transmission lines, during natural disasters. In this paper, the impact of microgrid clustering on their availability and stability will be studied.

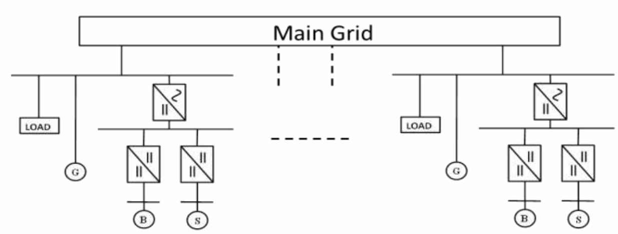

Figure 1. Microgrids clustering diagram.

II. HIERARCHICAL STRUCTURE OF INTERCONNECTED MICROGRIDS

In a cluster of interconnected MGs, one MG has to act as a slack bus to regulate the frequency. Preferably, this slack MG would have a rotating mass generator (e.g. diesel generator) with relatively high inertia and excess energy, to increase the stability of the group of interconnected MGs. The other microgrids connected at the different buses shall act as PV or PQ buses according to the type of resources they have, and their generated capacity compared to their local load demand.

In case of a blackout, each MG has two passive islanding detection mechanisms [2] at the PCC, one of them is voltage detection, i.e. if the voltage exceeds ± 5% of the nominal voltage [3], this passive voltage detection islands the MG. The other detection mechanism measures the rate of change of frequency (ROCOF). When this rate increases beyond a certain limit [3], the ROCOF relay islands the MG.

As shown in Fig. 2 and Fig. 3 all MGs should be able to communicate with each other in case of a blackout. When the MGs are islanded due to a power outage, they will communicate with each other to confirm and get acknowledgment that all of them detected the blackout. The preset control sets up the MGs to connect to each other by making one of them act as a slack bus or the master MG, and the others as slaves. The main controller evaluates which of the MGs has more energy and can make the cluster of MGs more stable. After this assessment has been done and a decision has been taken by the main controller, the connection between the MGs takes place throughout the designated infrastructure. The interconnected MGs have the option to supply the emergency loads between the interconnected MGs (loads at other buses external to the local MG) if they have excess energy, or isolate all the loads between them. The decision of which type of connection should be pre-decided based on the capacity of each MG and the amount of excess energy it might have, and the capacity of the emergency loads between the MGs.

Such a scenario will require a fully functional smart grid that has highly reliable communication system and predetermined control techniques [4], [5]. It also requires strong coordination between the DNO and the MG cluster. This is essential to protect the microgrid infrastructure when the grid gets back to service. In this paper, the behavior of two MGs connected to the IEEE 13-Bus standard distribution feeder [6]-[8] will be investigated to evaluate the impact of a blackout on the performance of both MGs when they are interconnected versus the case when they operate independently. Another study was dedicated to show the impact of generator inertia on the stability of interconnected MGs.

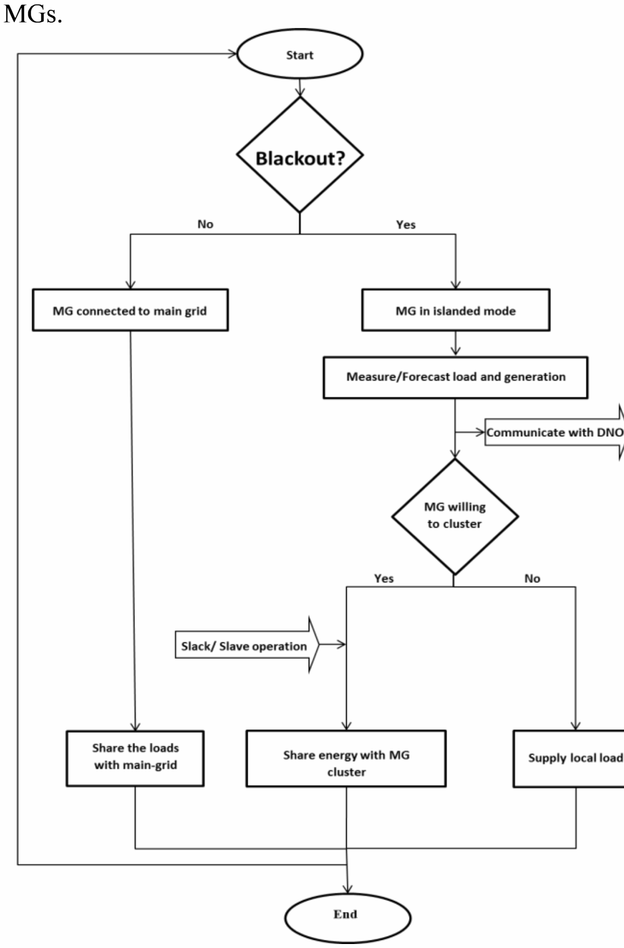

Figure 2. Individual microgrid control sequence.

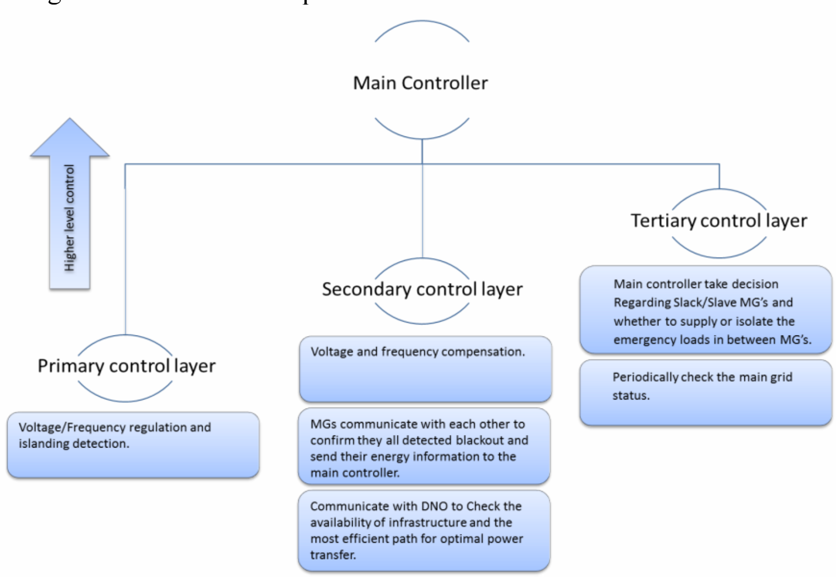

Figure 3. Microgrid cluster control hierarchy.

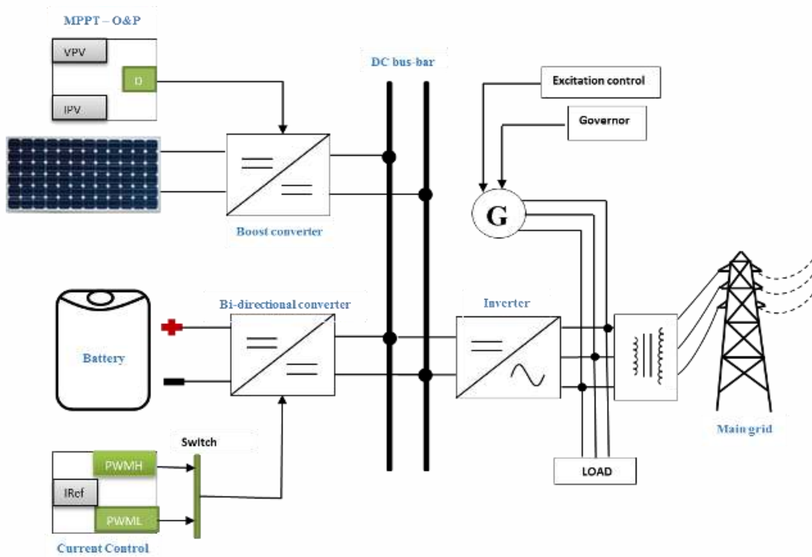

Figure 4. A block diagram for the microgrid under study.

III. Model Topology

In order to analyze the impact of microgrids clustering during blackouts, a case study was simulated. This simulation was based on the occurrence of a blackout in the main grid while two MGs interact with it, under different connectivity scenarios. The system was simulated in MATLAB® Simulink® environment. The main components of the example system include:

- IEEE 13 bus
- Two DC Microgrids each include:
  - 300 KVA diesel generator
  - 100 KW photo voltaic panels
  - 50 KW batteries
- Loads
- Primary controllers with islanding detection capability
- Secondary controllers, i.e., one for each MG
- Main tertiary controller, as shown in Fig. 3

The islanding detection was implemented at the point of common coupling between each microgrid and the main grid to island the MG in case of blackouts. Blackouts in this simulation were executed by opening a three-phase circuit breaker after the main substation of the IEEE 13 bus to simulate a three-phase short circuit fault that leads to a blackout.

Each DC microgrid [8] implemented in this design contains three main components as shown in Fig. 4:

- A photovoltaic system connected to the common DC bus through a DC/DC boost converter [9] controlled by a Perturb & Observe maximum power tracking (MPPT) technique [10].
- A battery bank connected to the DC bus through a bidirectional DC/DC converter [9] using a PID current control technique.
- A diesel generator connected directly to the AC bus, using an AC1A excitation system [11], to maintain the terminal voltage fixed, and a governor to regulate the mechanical input power to maintain 60 HZ.

IV. Case Studies

A. Case One: Non-Connected MGs

In this case, the simulation starts in the steady state mode as both MGs are already connected to the 13-Bus system. A blackout happens after 7 seconds. Each islanded passive detection mechanism for each MG senses the fault and disconnects the MG from the main grid, since the microgrids are disconnected from each other, each will function in an islanded mode trying to supply the demanded energy required by its local loads.

After 10 seconds, an effect of a cloud passing by blocking the irradiance from reaching the solar panels of MG-1 was simulated to investigate its capabilities to support its loads independently while the batteries weren't charged.

B. Case Two: Connected MGs

In this case, the two MGs are connected during the blackout forming a cluster of interconnected MGs trying to support the same loads they had as in case one, under the same conditions simulated before (i.e. blackout at the seventh second, and a cloud passes by MG-1 at the tenth second).

C. Case Three: Impact of Generator Inertia on Microgrid Cluster

In case three, with no cloud passing, the blackout takes place after six seconds. In this case, the impact of generator inertia on the power transferred from MG-2 to MG-1 will be shown.

V. Results and Discussion

A. Case One Results

Before the blackout happens, both MGs were stable while sharing their loads with the main grid before the blackout occurred as shown in the green circles before seventh second.

After the fault occurred at the seventh second, each MG supports its own loads independently where the electrical output P_e of each generator increases suddenly to balance this sudden change in the loading as shown in the red circles in Figs. 5(c) and 5(d), and their speed decreases momentarily as shown in Figs. 5(e) and 5(f) in the red circles, The output of each generator P_e decreases gradually with the gradual increase in the irradiance to provide the load with the fixed power it needs, however MG-1 starts to fail to support its own loads as shown in Fig. 5(c), while MG-2 goes to steady state due to the reduced loads on it as shown in Fig. 5(d).

At the tenth second, a cloud passes over the PV of MG-1 as shown in the black circle in Fig. 5(a), leaving the generator of that MG handling the whole load alone, which aggravates the problem and P_e goes to zero, since the loads were too large to be supported by the generator, it led the generator to fail. This consequently leads to rotor disturbances, which reflects on the output power that oscillates by the end as shown in the purple circles for MG-1.

The red circles in Figs. 5(a) and 5(b) depicting the output of the inverter show that the electrical output of the inverter of both DC MGs is affected by the disturbance due to the blackout. Moreover, the purple circle in Fig. 5(a) shows that the electrical output of the inverter was affected by the collapse of the generator in MG-1, that is because the inverter's controllers of the two MGs receive AC current and voltage signals from their sensors that are located at the AC bus-bar, in addition to a voltage signal from their local DC bus, to perform vector decoupling control on the output active and reactive power independently [12]. In islanded mode, the generator replaces the grid, and the voltage and current of the generator of the MG directly impact the output power profile of the inverter.

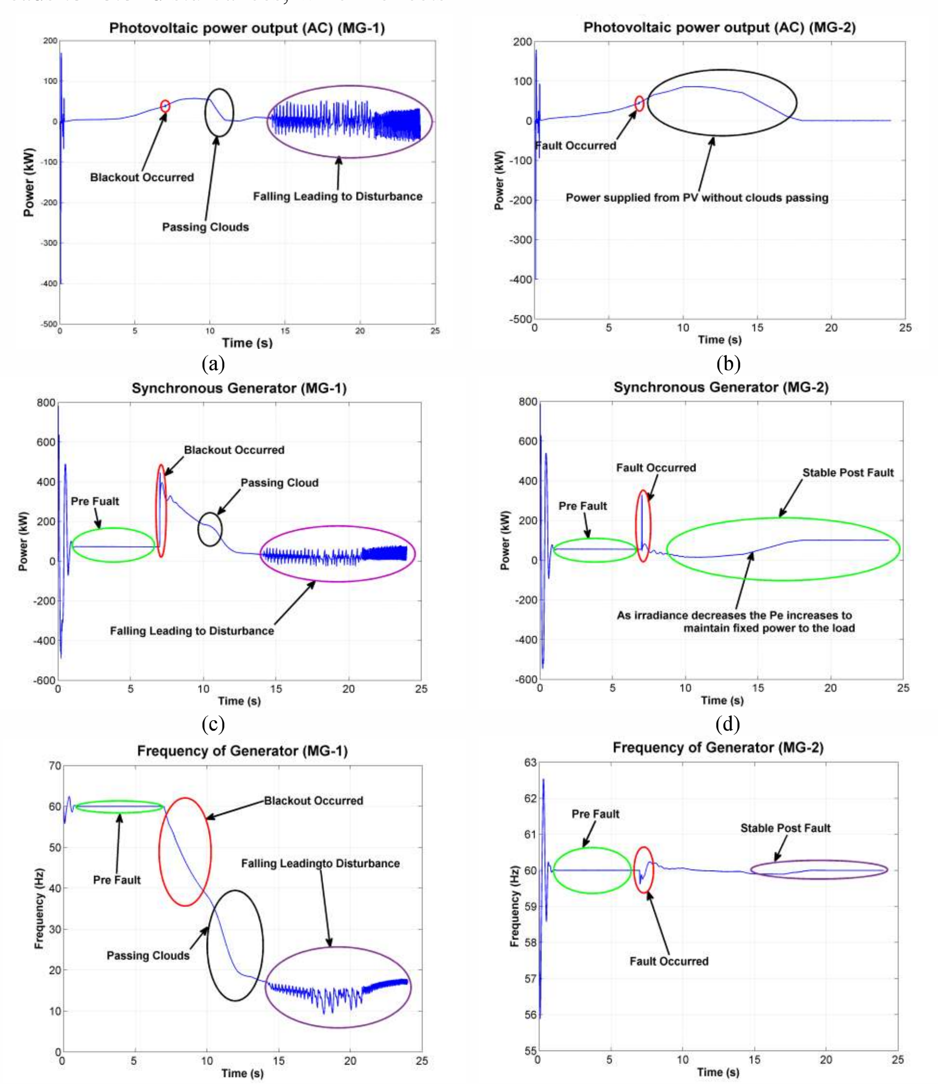

Figure 5. Results of Case I, (a) Inverter electrical power output of MG-1; (b) Inverter electrical power output of MG-2; (c) Generator electrical power output of MG-1; (d) Generator electrical power output of MG-2; (e) Generator frequency of MG-1; and (f) Generator frequency of MG-2.

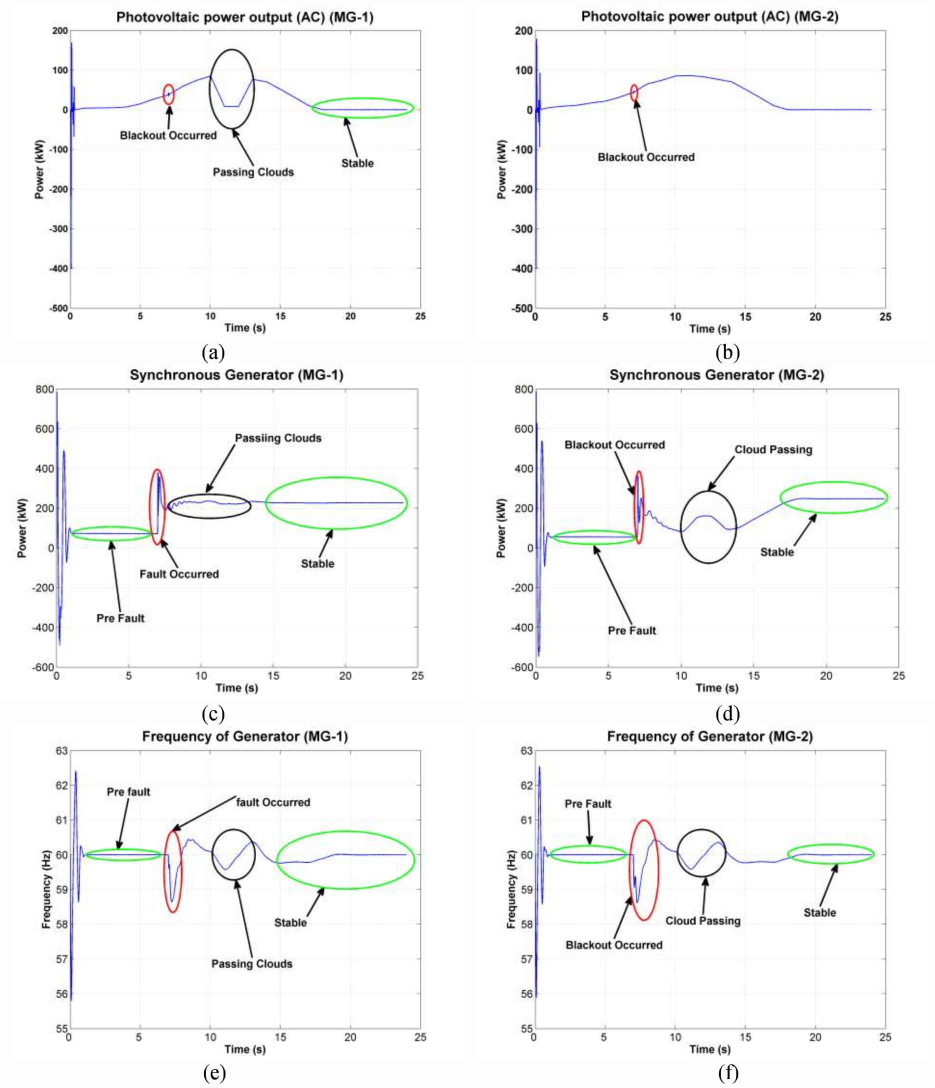

Figure 6. Results of Case II, (a) Inverter electrical power output of MG-1; (b) Inverter electrical power output of MG-2; (c) Generator electrical power output of MG-1; (d) Generator electrical power output of MG-2; (e) Generator frequency of MG-1; and (f) Generator frequency of MG-2.

B. *Case Two Results*

As shown in Fig. 6 below, the two DC MGs are stable while sharing the loads with the main grid as shown in the green circles, similar to the previous case.

At the seventh second at the moment of blackout, the two MGs are islanded. Then they communicate with each other to confirm that they all detected the blackout, and communicate with the DNO, then connect to each other through the infrastructure of the main grid and isolate all the loads in between. MG-2 act as a slack bus as it has more excess energy, while MG-1 acts as a slave by fixing its mechanical input to 0.95 pu as shown in Figs. 6(c) and 6(d).

When the clouds passes by the PVs of MG-1 as shown in the black circle in Fig. 6 (a), the generator of MG-2 increases its electrical output power P_e to cover this decrease in power from MG-1 due to that cloud as shown in the black circles in Fig. 6 (d).

Finally, when the power of PVs of the two MGs goes to zero, the generator of MG-2 increases its power to provide the loads with its required energy as shown in the green circle toward the end in Fig. 6(d).

The frequencies of the two generators are related, since the generator in MG-1 is following the generator in MG-2 (slack bus) Figs. 6(e) and 6(f). When the cloud passes by MG-1, the frequency drops as shown in the black circle in Fig. 6 (a) because the loading increases on the generator of MG-2 and consequently its speed decreases.

The power transferred from the generator of MG-2 varies with the output power of the PV of MG-1. As the irradiance increases gradually, the power transferred from MG-2 decreases gradually and vice versa. When the clouds pass by MG-1, the generator of MG-2 sends more power to the loads of MG-1 as shown in the black circle in Fig. 7. Towards the end of the 24-hour irradiance that was simulated by 24-seconds in the simulation, the generator of MG-2 keeps increasing the energy sent to MG-1 until it reaches its maximum when PV output is zero at night, as shown in the green circle by the end in Fig. 7.

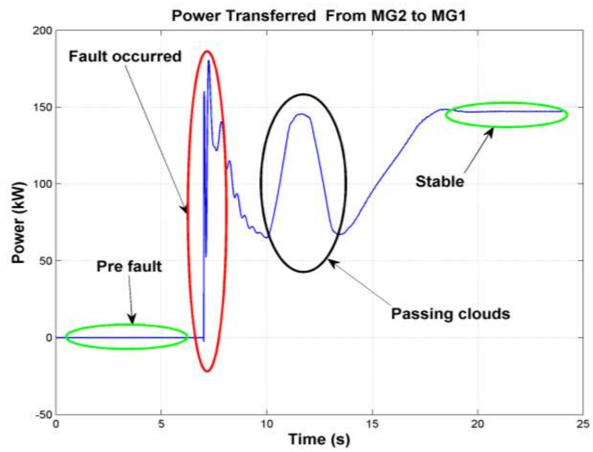

Figure 7. Case II: Power transfer during microgrid clustering.

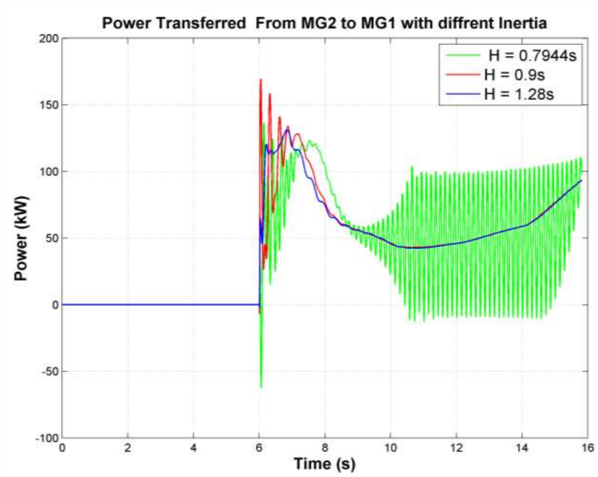

Figure 8. Case III: Impact of generator inertia on microgrid cluster.

C. Case Three Results

In Fig. 8, the power transferred between the two MGs under the same conditions (but no passing clouds), with different values of generators inertia, is depicted.

During the first six seconds, no power is transferred between the two MGs, once the blackout occurs and the main controller establishes a connection between the two MGs, the power starts to flow from MG-2 (act as a slack generator) to MG-1 that has more loads.

As noticed from Fig. 8, as the inertia of the two generators of both MGs increases, the microgrid cluster becomes more stable, also it is shown that at relatively low inertia (H=0.79) at the moment of blackout, the generator of MG-2 that sends the power to MG-1 starts to oscillate and becomes unstable, driving the whole system of the two MGs to be less stable. The generator different inertias were selected from industrial catalogue for the same size [13].

VI. CONCLUSIONS

During blackouts, independent MGs may fail to support their own loads individually, especially when they are highly dependent on renewable resources (e.g. solar panels) that are affected directly by weather variations (e.g. cloud passing by blocking the irradiance from the sun), however if the same MGs are interconnected forming a cluster of MGs using reliable communication and proper control, they can handle such variation better and in a more stable way.

The transferred power between the interconnected MGs is more stable when the inertia of both generators in the MGs is relativity high. At the moment of blackout, generators with low inertia tend to oscillate and may lead the whole microgrid cluster to be unstable. When interconnecting islanded MGs, it is recommended to connect MGs with rotating masses that have high inertia to increase the stability of that group of MGs.

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