Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Preventing Delayed Voltage Recovery with Voltage-Regulating Distributed Energy Resources

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***Abstract* -- With the large use of residential air conditioner (A/C) motors during the summer peaks, the potential of motor stalling events have increased in the recent years. The stalled motor loads have been found to be the most important cause of delayed voltage recovery following severe system disturbances, such as a subtransmission fault. The proper modeling of the stalled motors is a very important factor in identifying the effect of these motors in voltage recovery after the fault.**

This paper presents a methodology for modeling the stalled low inertia induction motors based on a sample utility system and a small primary distribution circuit. The prevention of the stalling of motors plays an important role in maintaining the voltage profile of the system after system disturbances. Distributed Energy Resource (DER) is used to prevent the motor stalling events so that the delayed voltage recovery of the system may be avoided.

***Index Terms* – induction motor modeling, stalled A/C motors, micro-voltage collapse, distributed energy resources, delayed voltage recovery.**

I. INTRODUCTION

Load modeling is a very important part of power system studies in order to simulate the dynamic behavior of the system. With the presence of a large amount of high efficiency induction motors based air conditioner (A/C) compressors, the system will be prone to micro-voltage collapse because these induction motors can enter the stalled mode and draw huge amounts of reactive power following severe disturbances. It is, however, difficult to accurately represent the behavior of these dynamic loads unless their characteristics are properly modeled under the severe disturbance such as a three-phase to ground fault. The characteristic events of micro-voltage collapse were observed in the Southern California Edison (SCE) system in the summer of 2004 [1] and the Western Electricity Coordinating Council (WECC) system in August, 1996 [2]. Similar events have been observed in the Metro Atlanta area in July of 1999 [3]. A few delayed voltage recovery events on different utility systems are summarized in [8]. The frequency of occurrence of delayed voltage recovery events in many utility systems has led to many research effects concerning the proper modeling of stalled induction motor loads in order to accurately represent these actual events into the simulation platform.

The modeling of stalled A/C motors of the Valley Substation of Southern California Edison (SCE) based on the PSLF program is carried out in [1]. The modeling considers a composite load model with 27% of residential A/C loads and 15% of three-phase motor loads in order to match the 2004 SCE summer event. A composite dynamic load model comprised of 80% static loads and 20% dynamic induction motor loads is considered for the study in the Western Systems Coordinating Council (WSCC) system in [2]. Testing on high-efficiency air-conditioning (A/C) units of [3] shows that the central A/C units decelerate and enter the stalled mode at fault voltages below approximately 70% of the nominal voltage independent of the fault clearing time. This current paper considers uses these test results to simulate the behavior of stalled motors.

The practical transmission system response with a large penetration of A/C compressor motors following the multiphase fault is simulated in [5] using induction motor models to represent the characteristics of compressor motors. The paper also discusses the effect of the multiphase faults and high A/C loads on the system voltage recovery. The developed methodologies for modeling the stalled motor loads for voltage stability analysis are presented in [6, 7]. In [7], the impact of induction motor load dynamics on the voltage recovery phenomenon is discussed using a quadratized power flow model.

Along with the modeling of dynamic loads of the system, another challenge lies in the development of the methodology to prevent such events from happening. With the wide and growing use of Distributed Energy Resources (DERs) in the modern power systems, the use of DERs in preventing such events would be a great achievement in this field. The effect of fast acting generator controls and reactive power support devices like the static Var compensator (SVC), Static Synchronous Compensator (STATCOM) and Superconducting Magnetic Energy Storage (SMES) in preventing a voltage collapse caused by stalled motor loads is presented in [8]. The inverter-based Distributed energy

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This research was sponsored by the Office of Electricity Delivery & Energy Reliability, U.S. Department of Energy (http://www.oe.energy.gov/) under Contract No. Contract No. DE-AC05-00OR22725 with UT-Battelle and conducted at Oak Ridge National Laboratory (ORNL) and University of Tennessee.

978-1-4244-2235-7/09/$25.00 ©2009 IEEE

resources (DER), which are capable of producing both active and reactive power with the help of its power electronics interface in a minimum cost as compared to a much more expensive STATCOM, have been proposed in [9]. This paper uses the DER proposed in [9] to simulate how it can prevent the voltage collapse due to the stalled air conditioner loads.

This paper first introduces the modeling of the stalled induction motor loads using an example utility system. The methodology adopted in this case is applied to a representative radial primary distribution feeder to show the effect of DER on the system voltage control.

The remaining part of the paper is organized as follows: Section II describes the assumptions and methodology adopted in modeling dynamic motor load response in the event of a three-phase fault. Section III describes the modeling of the DER. Section IV presents the test systems used and the results obtained from simulation. Section V summarizes the major contributions of the paper.

II. Assumptions and Methodology for Induction Motor Modeling

The modeling of the residential loads is done based on different load compositions e.g. Air-conditioning (A/C) motors, constant impedance loads, constant power loads and normal three-phase motor loads. The distribution of load among different components is done to mimic the real-world diversity of distribution of loads.

The basic underlying assumptions and the methodology for the development of induction motor models to reveal the response and actions of motor stalling during a system disturbance, such as three-phase line to ground fault. is described in this section. The assumptions are mainly based on the behavior of induction motors from actual case data and from testing of A/C units at low voltage and high temperatures as described in the earlier references.

Assumptions:

1. According to the test results on A/C motors provided by SCE, A/C motors can stall in as little as 3 cycles [1]. This time is considered the benchmark for the transition of the induction motors to the stalled mode.
2. The voltage magnitude criterion for the induction motors to enter the stalled condition is below 0.7 per unit. If the voltage at the induction motor terminal is below 0.7 per unit for 3 cycles or more, the motors enter the stalled mode.
3. Once the A/C units stall, they remain stalled until they are eventually tripped out of the system by thermal relays.

Methodology:

In the MATLAB platform, the Asynchronous Motor model and constant power model of the SimPowerSystem library is used to model the A/C units in the normal mode for Cases A and B described below respectively. If the voltage at the motor terminal falls below 0.7 p.u. for 3 cycles or more following the fault, the induction motor model switches to the constant impedance load model during which the stalled complex power increases 6 times that of the normal mode of operation. The power factor considered for the normal mode of operation is 0.88 and 0.58 for the stalled mode.

The flowchart of the overall methodology used to model the induction motor loads for normal and stall operation is presented in Fig. 1.

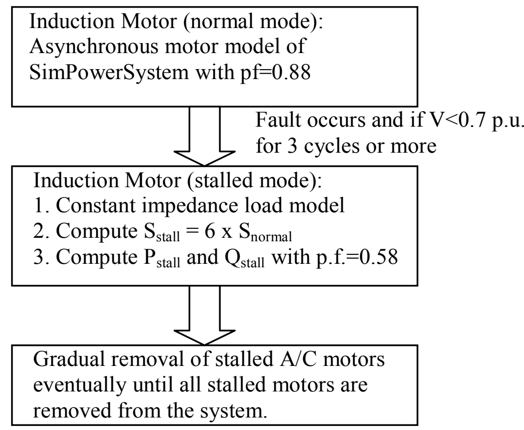

Fig. 1. Overall methodology of load modeling.

III. Methodology for DER Modeling

Distributed Energy Resources (DERs), which are modular small power systems of the size roughly 10 MW or less, are connected at the substation, distribution feeder or end-user customer load levels. They can be either generator or inverter-based systems. DERs sized from 50kW to 500kW are assumed in the present research. However, several small DERs were aggregated into one model connected at a single bus. Figure 2 shows the basic power electronics interface connection topology of the DER to the utility grid. Since most of the DERs are dc power sources like photovoltaic and fuel cells, a power electronics interface which can convert the dc power to ac power is required for the grid connection. The interface is needed to provide ac power of desired waveform, frequency, magnitude, and phase angle may be obtained.

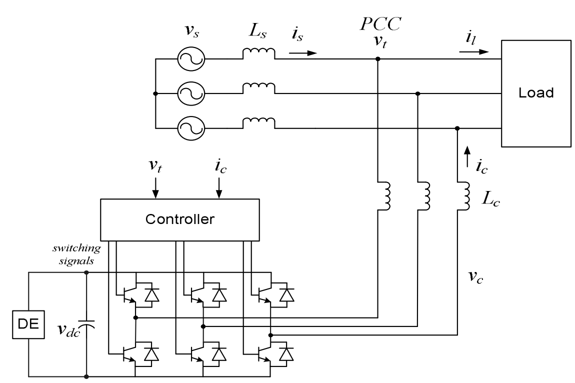

Fig. 2. Parallel connection of a DER with power electronics converter.

In the figure above, the DER is connected to the utility grid via inverter which converts the dc power from the DER to ac power. The inverter is connected to the grid in parallel through the coupling inductor, L_c. The rest of the system is simplified as an infinite utility voltage source with a system impedance of $j\omega L_s$, neglecting the resistance. The inverter is connected to the utility grid at the point-of-common coupling (PCC) and the PCC voltage is denoted as v_t. The PCC voltage v_t and the inverter current i_c are measured and provided to the controller. In this case, it is assumed that the DER produces only reactive power and that the reactive power provides local voltage regulation (the PCC voltage is controlled at a reference level).

IV. SIMULATION RESULTS

This section encompasses the simulation results by modeling the normal and stalled induction motor loads with a mix of constant impedance and constant power loads. Two cases have been considered for the study. Case A provides simulation results for A/C motor behavior before and after the fault. This case does not consider the installation of any DER into the system. In this case, induction motors prior to the fault are modeled using the asynchronous motor model of the Matlab SimPowerSystem library. The methodology adopted in Case A is used to model the loads in Case B. The simulation results of Case B show how the DER can help the system voltage recovery. In this case, induction motors are modeled as constant power dynamic loads prior to the fault.

Case A: Motor load characteristic during sub-transmission fault considering aggregate load model

The system configuration is as shown in Figure 3. The complete load composition for this case is shown in Table 1. These test data are extracted from [1] for benchmarking the simulation.

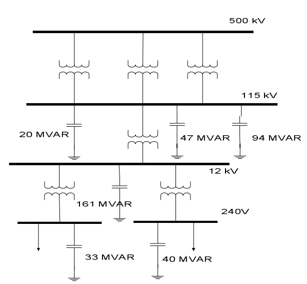

Fig. 3. System configuration for Case A.

Table 1. Load composition for Case A.

	Constant Power (33.6%)	Constant Impedance (21.9%)	3-phase Motor (15.6%)	Residential A/C (28.8%)
MW	320	209	133	246
MVAR	0	0	66	121
PF	1.0	1.0	0.9	0.9

This case demonstrates the stalling behavior of induction motor loads in the event of severe faults. For the simulation of this system, the following assumptions were made [1]:

1. A three-phase to ground fault is applied at 0.5 seconds at the 500kV bus.
2. The fault is cleared in 4 cycles
3. One of the 500kV/115kV transformers is isolated once the fault is cleared
4. The loads are represented by an aggregated load model for all types of loads, e.g., A/C loads, three-phase motor loads and constant impedance loads.
5. All induction motors stall if the voltage is below 0.7 p.u. for 3 cycles or greater.
6. The stalled three-phase motors are tripped out (load removed) by thermal relays in six cycles after the fault.

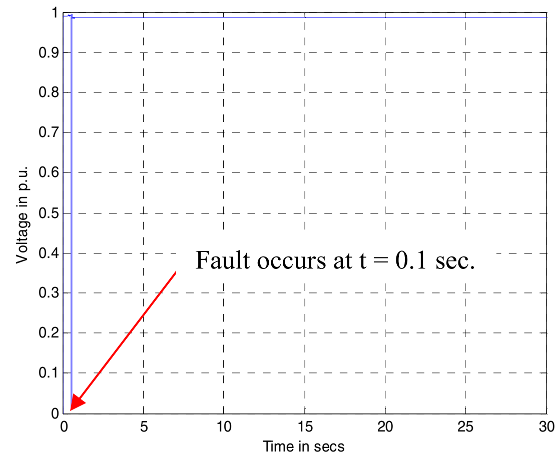

Fig. 4. Voltage profile of bus 115kV without modeling of stalled case.

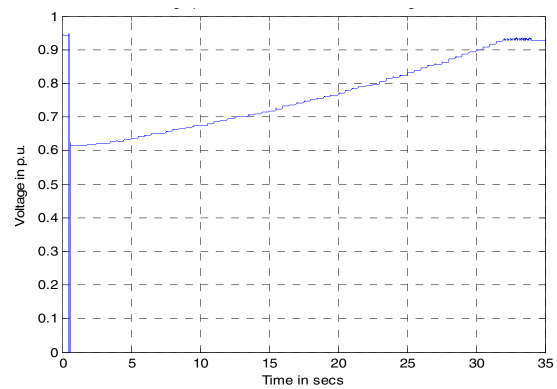

Fig. 5. Voltage profile of bus 115kV after modeling the stalled motors.

Figure 4 shows the voltage profile at the 115kV bus using the load composition as shown in Figure 3 and Table 1 without the model of the stalled motor loads. The figure clearly shows that the voltage recovers quite quickly after the fault is cleared. The effect of A/C motor stalling is not visible since it is not represented. Figure 5 shows the voltage profile at the 115kV bus using the load model of Figure 3 and Table 1 when the stalled induction motors are modeled based on the methodology described in section II. The voltage profile clearly shows the effect of induction motor stalling with the delayed voltage recovery. Once the fault is cleared, the voltage recovers to around 0.6 p.u. but is not able to recover to the original value as quickly as in the first case. All the motors enter the stalled mode 3 cycles after the fault and remain stalled because the voltage cannot recover quickly to its before fault value. The tripping of the residential A/C motors starts at 2.5 seconds which has been carried out manually in the current model using three-phase circuit breakers assuming that the A/C unit thermal relays start tripping from that time onwards. A small percentage of induction motor loads (A/C motors) is taken out of the system over time in small intervals to mimic the different time delays of the thermal relays [1]. As the stalled motor loads are taken out of the system, the voltage profile at the 115kV bus gradually increases to its original before fault value.

Case B: System with 10 MVA loads in 13.8 kV feeder

The next case considered is the one with a total of 10 MVA of loads in a 13.8 kV feeder with the fault occurring at the 115 kV bus. The system configuration is shown in Figure 6. A single DER is connected to the 13.8 kV feeder via a 208V/13.8kV distribution transformer. The DER is an aggregated model of many small DERs. For instance, considering the future high penetration of roof-top photovoltaic system of 10 kW each, we will have about 600 units such that the total DER real-power capacity is close to the 6MW load. Because the DER model and its control system model only reactive power control, a real power source of 6MW is placed at Bus 2 along with the DER in order to mimic real power injection in addition to reactive power injection from the DER. The current limit is not fully enforced, so we can investigate how much reactive current is needed to improve the fault voltage to above 0.7 p.u. in 3 cycles such that the A/C motors will not enter the stalled mode. It should be noted that the aggregate DER is placed at the mid-point, i.e., Bus 2 in the 13.8 kV feeder, because the actual 600 DERs are likely to be distributed in the feeder evenly. So, it is reasonable to put the aggregated DER at Bus 2 rather than Bus 1 or Bus 3. It should be noted that we assume that the DER will not be disconnected within 0.1 seconds after the fault occurs because our intention is to investigate the possibility for the DER to inject enough reactive current to help distribution feeders ride through a temporary fault. It should be also noted that here a three-phase 208 V secondary distribution system is assumed to model an aggregate DER representing many small three-phase or single-phase DERs, although in practice the system may be 480 V three-phase and/or 120/240 V split phase in the U.S.

The load composition for this system is given in Table 2. The composition of residential A/C is considered to be 50% to represent the worst case scenario. The remaining loads are comprised of constant current loads and constant impedance loads. Both categories of loads have a power factor of 0.9 lagging at 1.0 p.u. voltage.

Table 2. Load composition for Case B.

	Constant Current (30%)	Constant Impedance (20%)	Residential A/C (50%)
MW	2.7	1.8	4.4
MVAR	1.3	0.871	2.37
PF	0.9	0.9	0.88

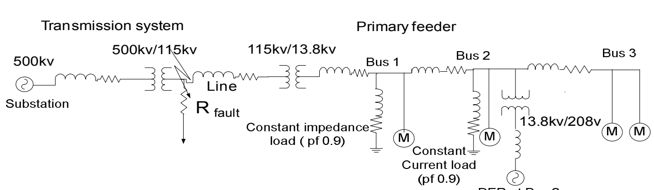

Fig. 6. System configuration with 10 MVA loads.

For this case, the simulation is carried out for the case with and without DER at Bus 2. As shown in Figure 6, the fault is applied at the 115 kV bus at 0.1 seconds and cleared at 0.2 seconds. Figure 7 shows the Bus 1 voltage profile for the simulation without DER. Without the reactive power support from the DER, the A/C motor loads enter the stalled mode so that the voltage cannot recover quickly to the pre-fault value. The voltage recovery is delayed as shown in the figure, and the final voltage recovers to a value slightly above the original value because of the tripping of A/C motors. Similarly, Figures 8 and 9 show the voltage profile at Bus 2 and 3 respectively. The Bus 3 voltage profile, before, during and after the fault is the lowest among the three buses as this bus is at the farthest end of the feeder.

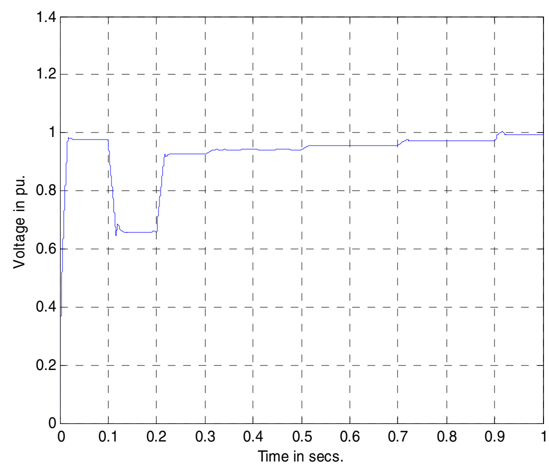

Fig. 7. Voltage profile at Bus 1 without DER.

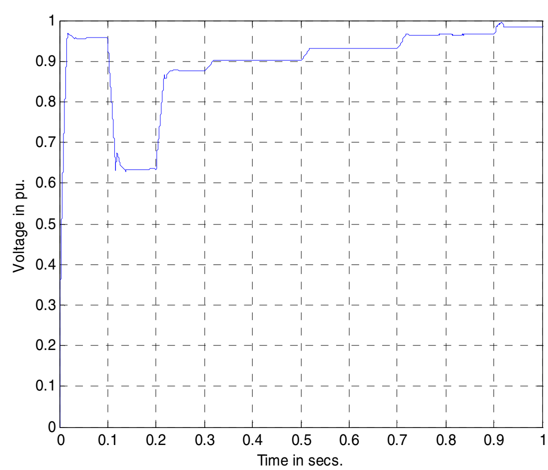

Fig. 8. Voltage profile at Bus 2 without DER.

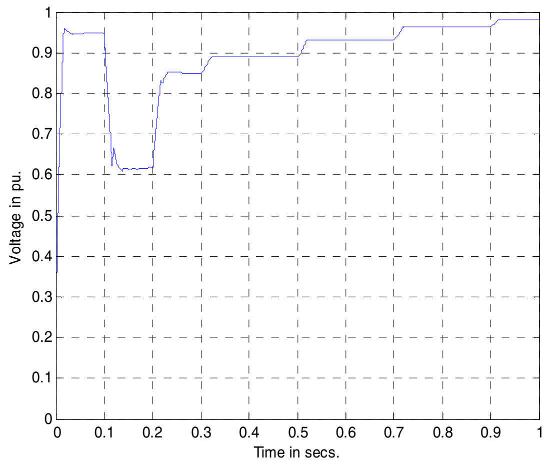

Fig. 9. Voltage profile at Bus 3 without DER.

Next, the case with the DER installed at Bus2 is simulated to observe the effect of preventing the A/C motors from stalling. Figures 10 through 12 show the voltage profile at Bus 1, 2 and 3 after the fault when the DER is installed at Bus 2. With the DER present, the motors do not enter the stalled mode and continue operating in the running mode. Comparing the voltage profile of the different buses without and with DER, it can be seen that the fault voltage is slightly above 0.6 p.u., and has been boosted to above 0.7 p.u. in around 3 cycles in each case because the A/C motors do not stall so that the voltage quickly recovers to its original value almost immediately after the fault clears.

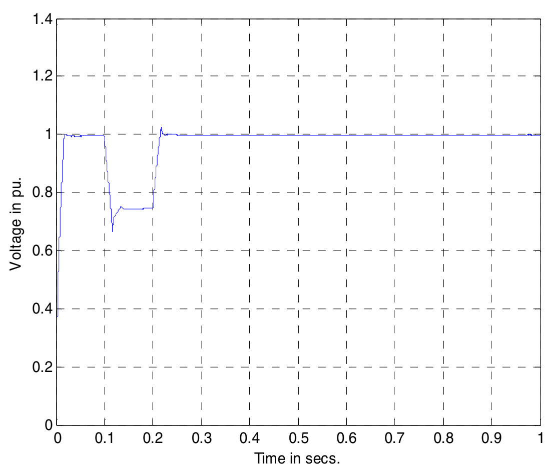

Fig. 10. Voltage profile of bus1 with the aggregate DER connected at Bus 2.

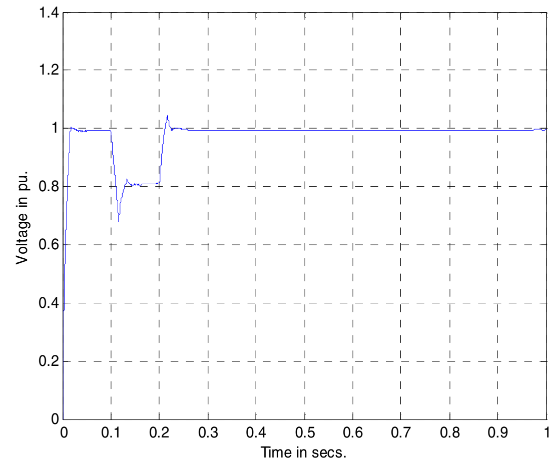

Fig. 11. Voltage profile of Bus 2 with the aggregate DER connected at Bus 2.

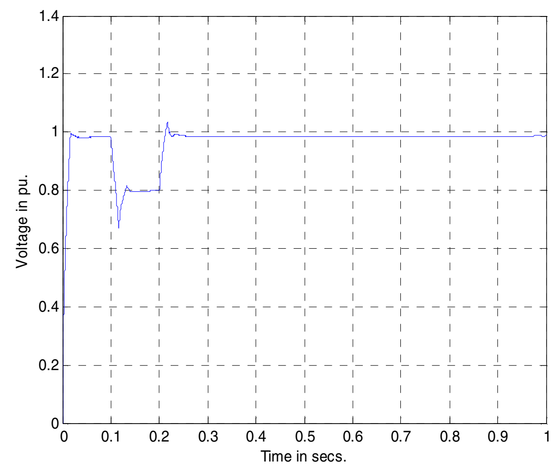

Fig. 12. Voltage profile of Bus 3 with the aggregate DER connected at Bus 2.

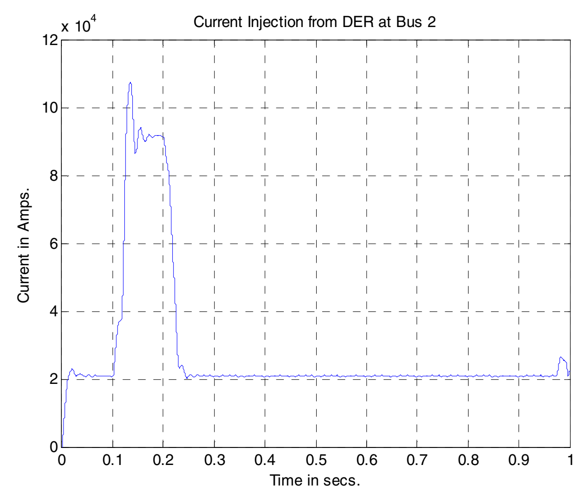

Fig. 13. Injection current from the DER inverter.

Figure 13 shows the per phase current injection from the inverter. It can be seen from the graph that a large amount of reactive current injection is required to correct the voltage due to the fault to be above the stalled voltage trigger of 0.7 p.u. in order to prevent the induction motors from stalling. Once the fault is cleared, the current injection comes back to its original value. The maximum current injection of around 107 kA from the aggregated DER model connected at 208 V side for only around 3 cycles seems to be within a practical capability. Considering our assumption that the aggregated DER model represents 600 small DERs consisting of 10 kW roof-top photovoltaics, each small DER will inject 178A (=107,000/600) of reactive current for 3 cycles. This is technically feasible for each even with the available technology today. Certainly, cost is a present barrier for the large deployment of DER systems with inverter-based interfaces. However, with the optimistic estimation that the performance of power electronic inverters will continue to increase while the cost decreases, it is possible to have a high penetration of inverter-based DERs such that they can quickly correct voltage by injecting a large reactive current for a very short duration to avoid possible delayed voltage recovery. Again, it should be noted that here a three-phase 208 V secondary distribution system is assumed to connect an aggregate DER representing many small three-phase or single-phase DERs, although in practice the system may be 480 V three-phase and/or 120/240 V split phase.

V. CONCLUSION

This paper presents a methodology for modeling stalled induction motor loads using a composite load model in a Matlab SimPowerSystems platform. The simulation results of an example distribution system fed from the submission system show that the system voltage subjected to a severe disturbance like a three-phase-to-ground fault takes a certain time to recover to the pre-fault voltage level following the clearing of the fault. The delayed voltage recovery is because the induction motor load, which represents the A/C compressor motor loads, enters the stalled mode in as little as 3 cycles if the system voltage drops to less than 0.7 per unit. A corrective method using voltage-regulating Distributed Energy Resource (DER) is investigated which can aid in recovering the system voltage immediately after the fault. The simulation results show that DER has the potential to prevent the stalling of the A/C motor loads so that any micro-voltage collapse on the distribution system or major voltage collapse on the sub-transmission/transmission can be prevented in utility systems with a large percentage of A/C loads.

Future research may lie in modeling the dynamics of many small DERs, rather than an aggregated DER model in order to fully improve the distribution system capability to ride through delayed voltages due to faults. Also, the impact to other issues such as protective device settings and the actual implementation to keep DER connected for 0.1 seconds after a fault need to be investigated.

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