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Modeling and Simulation of Advanced Coordinated Control of Distributed Energy Resources with High Renewable Penetration

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SUMMARY

This paper presents and discusses modelling and simulation of advanced coordinated control of several distributed energy resources (DER) in a power grid with a high penetration of up to 60% of Photovoltaic (PV) generation. The DER under discussion includes a PV plant, a battery energy storage system (BESS), and several diesel generators. An auxiliary control model that implements an advanced control logic and interfaces and coordinates with a plant controller has been developed to achieve an advanced coordinated control of the DER. In this control scheme, the plant controller is configured to send appropriate commands to the PV and BESS to regulate their output. One main objective of the advanced coordinated control is to curtail PV output whenever necessary. In this paper, the generic models for the master plant controller, the BESS, and the PV, have been configured, parameterized, and tuned to maintain system frequency and power balance in the grid and to meet grid code requirements. Dynamic simulation results indicate that these configured and parameterized models perform as expected under different system contingency events. These models are appropriate for power system planning and operation studies.

KEYWORDS

Battery storage, contingency, energy curtailment, frequency regulation, power control, renewable energy, solar PV, reactive power control, system planning, voltage regulation.

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I. INTRODUCTION

Distributed energy resources (DERs), typically deployed on the distribution system, generally include battery energy storage system (BESS), plug-in electric vehicle applications, energy efficiency and demand response, solar photovoltaic (PV), combined heat and power or cogeneration systems, microgrids, wind turbines, micro turbines, and back-up generators such as diesel or gas turbines. Over the last decade, more and more DERs are being integrated into the power system. Integration of such DERs into the power grid poses challenges to power system planning, operation and control. This paper presents and discusses an advanced modelling approach of coordinated control of battery energy storage, solar PV, and diesel generators in a renewable energy project on a power system with high PV penetration. The models developed and presented are appropriate for power system planning studies. The project interconnects several DERs to the power grid. One interconnection requirement is the provision and submission of project's simulation models for approval and use for system planning studies. To meet this requirement, the project includes development of a new auxiliary controller model to implement an advanced control technique and to interface with a set of Western Electricity Coordinating Council (WECC)-approved 2nd generation renewable energy generic models. Such new and coordinated control models implemented for the project were tuned, verified, and submitted to the system operator for compliance with the interconnection requirement of the project. The submitted models were then approved for system planning and operation studies. The authors of this paper are not aware of any advanced coordinated control models such as the ones presented in this paper either in the published literature or real power system applications. To the best knowledge of the authors, this is the first submission of this type of coordinated control models to the system operator for a renewable energy project involving DERs. The submitted models were approved by the system operator and are appropriate for system planning and operation studies.

The subsequent sections discuss system configuration, DER control objectives, model development and implementation, advanced coordinated control of the DER, and representative dynamic simulation results.

II. SYSTEM DESCRIPTION AND CONTROL OBJECTIVES

A. System Description

The system under study includes a solar 4.5 MW PV plant, a 3 MW BESS and several diesel generators, all of which are connected to the 12.47 kV distribution network via appropriate step-up transformers. Fig. 1 shows a simplified one-line diagram of the system. The total load of the system is approximately 6 MW. The maximum output of the PV plant constitutes up to 60% of system total generation. One of the requirements of the advanced controller is to control and deliver constant active power to the grid. The BESS is rated at 3 MW/10 MWh. It operates in peak-shaving mode (i.e. charges the BESS during the day and injects energy back to the grid at night). In addition, the BESS can also provide grid security ancillary services such as such as fast response, contingency reserve, reactive power, and voltage support.

B. Controller Description

An advanced coordinated control system is designed and equipped with controllers at two levels: 1) The Primary Control which is a master power plant controller at system level, which coordinates and controls the PV, the BESS, and diesel generators to maintain specified system operating conditions (based on active and reactive power, voltage and/or frequency setpoints); 2) The Secondary Control which is based on device-level controller that are built in the PV and BESS for local frequency, active and reactive power control In addition, an advanced Auxiliary Controller maintains the power balance within the system by monitoring the total system load and the status of diesel generators, and adjusting the net active and reactive power out of the PV and the BESS. A detailed description of development of the Auxiliary Controller model is discussed in the next Section.

Diesel generators operate on their own exciters and governors. However, the master plant controller acts on the status or required minimum generation request from these generators to achieve power and reactive power control in the system. The control objectives for the system include:

1. Regulating system frequency and voltage.
2. Maintaining constant net active power into the grid from the PV/BESS plant (renewable output smoothing).

3. Reducing the PV output to maintain constant net power into the grid when the BESS trips (renewable curtailment).
4. Controlling active power and frequency when a diesel generator is out of service.
5. Controlling the reactive power into the grid from the PV/BESS plant with a constant proportion of total system load.

The project was designed to use a centralized controller to achieve the above control objectives since the DERs are geographically and relatively close to each other and they are also close to loads.

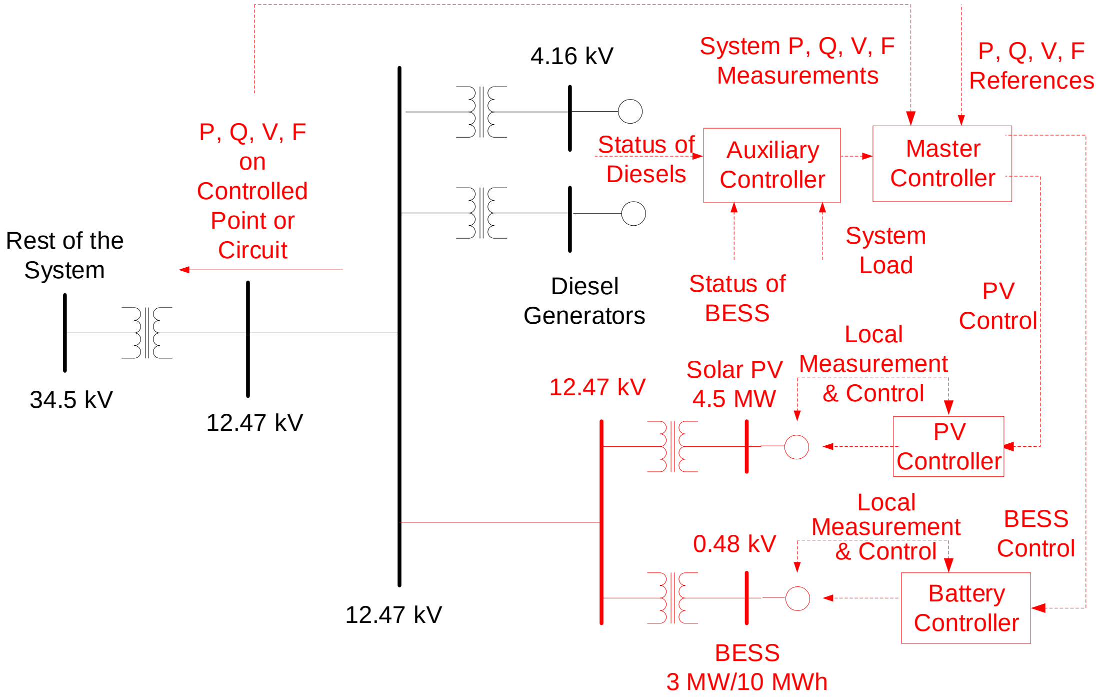

Fig. 1. One-line diagram of the distribution system including a schematic diagram of the coordinated control of DERs.

III. DEVELOPMENT, MODELING AND IMPLEMENTATION OF ADVANCED COORDINATED CONTROL

The advanced coordinated control depicted in Fig. 1 have been implemented using a set of WECC 2nd generation renewable energy generic models as well as a new auxiliary controller model developed by the authors. All model parameters were derived, calculated and tuned from the actual equipment characteristics and control system of the project, engineering experience and judgement. Modelling details are discussed below.

A. Modelling of the Master Plant Controller

The master plant controller was modelled using the WECC generic model REPC_B [1], whose block diagram is included in the Appendix of this paper. This model can control and coordinate with models for other devices or controllers such as:

1. Battery energy storage devices
2. PV inverters
3. Wind turbines
4. FACTS devices (e.g., STATCOM or SVC)
5. Synchronous condensers

In this implementation, the master plant controller model was configured to set to operate in a P-control mode. It measures system conditions (P, Q, V & F), processes target quantities through proportional-integral (PI) regulators and sends control commands to the auxiliary model that controls the PV and BESS to regulate the active power and frequency at the controlled point to be within a specified range. Parameters of the master plant controller were selected and tuned based on the actual control system designed.

B. Development of the New Auxiliary Controller Model

A new auxiliary controller model “NEWAUX” was developed to monitor the status of the diesel generators, the total system load, and the BESS, and to maintain frequency, voltage, and power balance within the system by adjusting active and reactive power out of the PV and/or BESS, when any of the diesel generators or the BESS is out of service. This new model interfaces with the master plant controller model and hence the PV and BESS models to adjust the output of the BESS or aid in the curtailment of the PV inverters, if necessary. Error! Reference source not found. shows the functional flowchart of the auxiliary controller model NEWAUX.

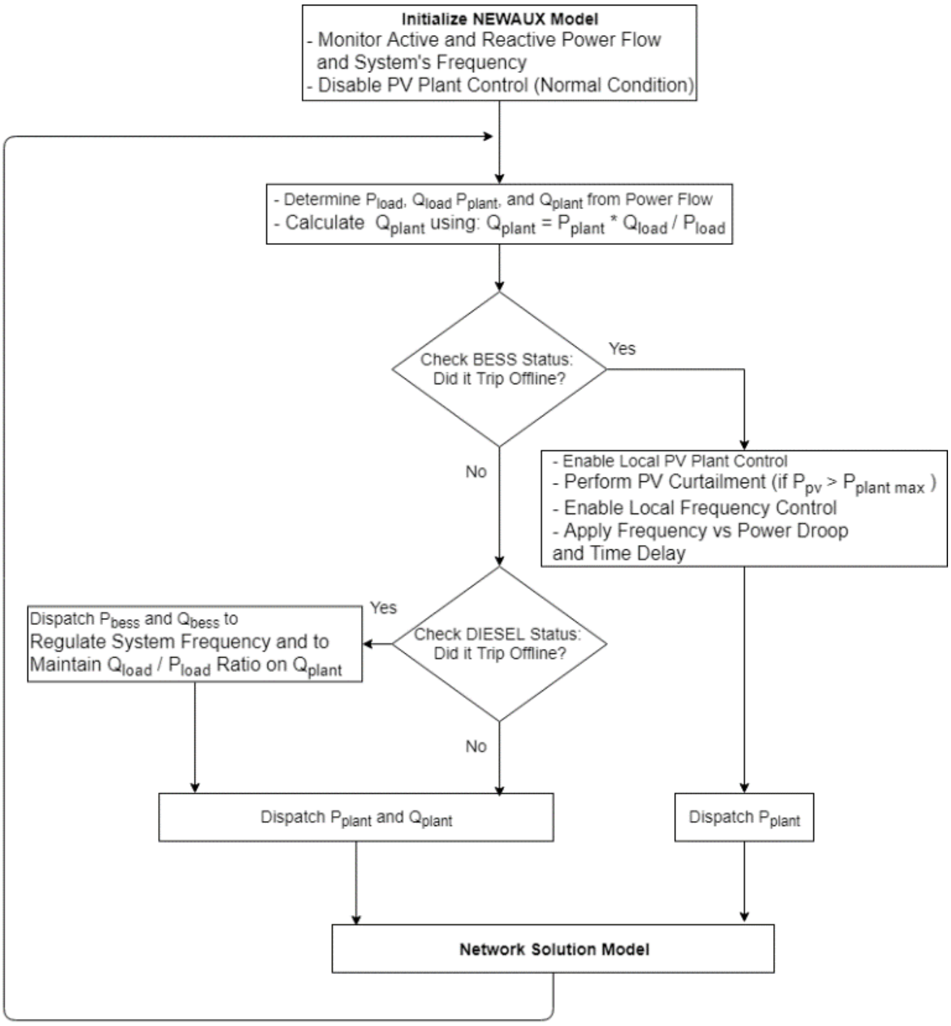

Fig. 2. Functional flowchart of the auxiliary controller model NEWAUX.

One control requirement is that when the BESS on the charging mode trips due to contingency events, PV production needs to be curtailed to maintain constant net power into the grid. PV curtailment is initially based on frequency droop control. When the system frequency exceeds a threshold for a preset time, the master control system sends a P-command to the PV to achieve curtailment. This auxiliary controller model implements this advanced control logic and interfaces between the plant controller and the PV/BESS system.

The Auxiliary Controller also interfaces with the Primary Controller and the Secondary Controller at the PV plant to aid in the curtailment of the PV inverters, and to enable local frequency control (based on a Frequency vs. Active Power droop), if necessary. This Auxiliary Controller continuously monitors the status of the BESS and sends a curtailment signal to the PV, if the BESS gets tripped offline.

C. Modelling of the PV Plant

The PV plant was modelled as a renewable generator using the WECC 2nd generation generic renewable system models including [2]:

1. REGC_A: Generator/converter model

2. REEC_B: PV electrical control model

Parameters of the PV plant models were selected from actual equipment characteristics, engineering judgement, or typical engineering values. The block diagrams of these generic models are included in the Appendix of this paper.

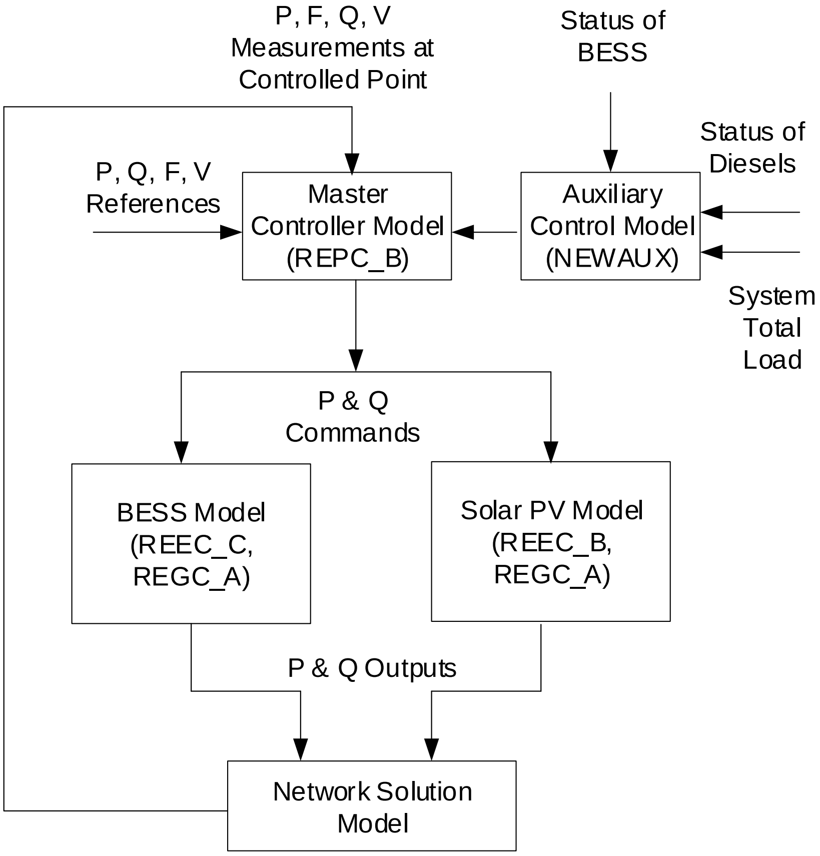

Fig. 3. Interaction diagram of the interconnected models of the master plant controller, auxiliary controller, PV and BESS controllers.

D. Modelling of the BESS

The BESS was modelled as a renewable generator using the WECC 2nd generation generic renewable system models including the following modules [3] [4]:

1. REGC_A: Generator/converter model
2. REEC_C: Battery storage electrical control model

REEC_C executes P and Q controls, monitors the state of charge (SOC) of battery and sets appropriate active current limits. In the implementation, P-priority control was selected for power and frequency control. Parameters of the BESS models were selected and tuned from actual device characteristics [5]. The block diagrams of these models are included in the Appendix of this paper.

E. Modelling of the Diesel Generators

The diesel generators were modelled as conventional generators with exciters and governors with the parameters based on actual equipment characteristics. These models (named GENSAL, EXBAS, and DEGOV) are standard library models in PSS$^{®}$E [6], a widely-used power system planning software tool that was also used to perform dynamic simulations included in this paper.

F. Data Flow and Model Interaction

Fig. 3 shows data flow and interaction of the interconnected models of the master plant controller, auxiliary controller, PV, and BESS. These coordinated control models were submitted to the power system operator for compliance with interconnection requirements for the PV and BESS and approved for system planning studies.

IV. DYNAMIC CASE STUDIES

The power system with the configured and parametrized generic models described in the previous section was simulated using PSS$^{®}$E to replicate various system scenarios and dynamic events in the system planning study. For illustrative purposes, only one system scenario and four dynamic events are discussed here. In all of these cases, the focus is on active power and frequency control. Fig. 4 shows the PSS®E one-line diagram of such system scenario. In this scenario, the system total load is about 2.2 MW. The PV plant is producing 2.3 MW in the steady-state condition. The MW flow on the controlled branch at the point of interconnection (POI) is required to be maintained at around 1.3 MW (a target value), which is about 60% of system total generation (a high PV penetration scenario). As such, the BESS is absorbing excess solar power of 1 MW (in the charging mode). The control system is configured to regulate the system frequency and the power flow at the controlled branch (i.e., PV net power into the grid) to be that target value. The frequency control is implemented with appropriate Frequency vs. Power droop and frequency deadband for all the simulation cases discussed below.

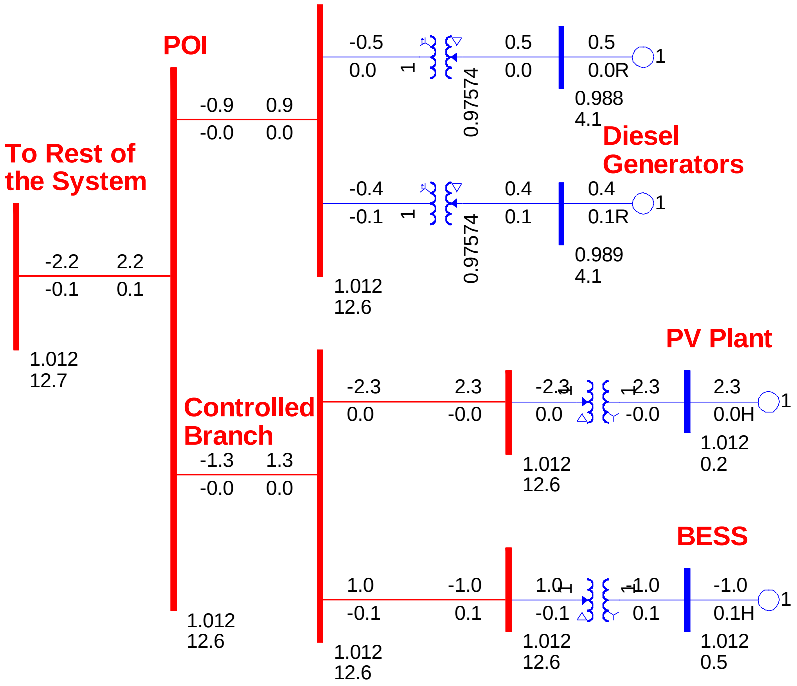

Fig. 4. PSS®E one-line diagram of the system under study.

A. *System Response to a Bolted Fault*

In this case, a 6-cycle three-phase fault was applied at the POI at 1 second into the simulation. Fig. 5 shows the responses of the system frequency (red curve) and controlled branch power (green curve) following the fault. Fig. 6 shows the responses of the PV power (red curve) and the BESS power (green curve) during and after the fault. During the fault, the PV enters a momentary cessation (zero power output) due to a very low voltage caused by the fault and the BESS power compensates for the PV power change such that the controlled branch power also reduces to zero due to a zero voltage at the POI. After the fault is cleared, the BESS regulates the system frequency with the appropriate droop and deadband as well as controls the branch active power to be the desired target value.

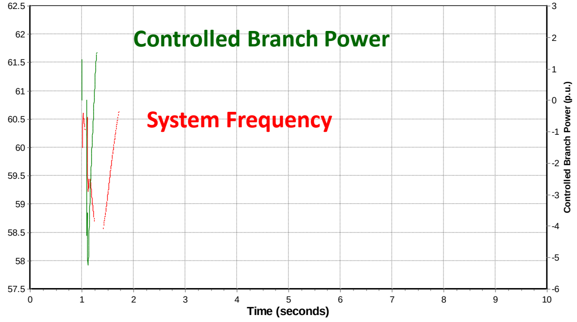

Fig. 5. Responses of the system frequency (left axis) and controlled branch power (right axis) following a fault.

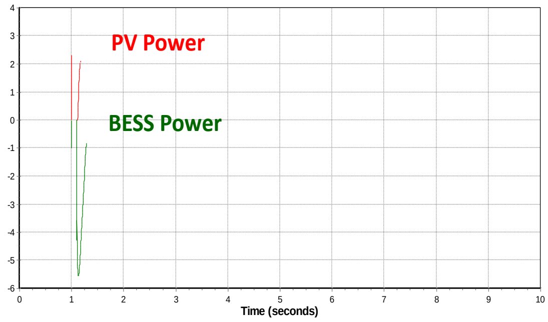

Fig. 6. Active power output responses of the PV and BESS (left axis) following a fault.

B. *Active Power and Frequency Control Following the Loss of a Diesel Generator*

In this case, one nearby diesel generator was switched offline at 1 second into the simulation. Fig. 7 shows the responses of the system frequency (red curve), controlled branch power (green curve), PV power (black curve) and BESS power (blue curve) following the loss of the diesel generator. The master plant controller detects the loss of generation and the system frequency change (with the deadband) and sends an appropriate P-command to the BESS electrical control model to adjust its power output and hence regulates the system frequency and controls the active power flow on the controlled branch at the POI to be at the pre-disturbance value (1.3 MW). The PV power was configured to be uncontrollable in this case as is the case in most system applications.

C. *PV Production Changes due to Cloud Movement*

In this case the PV production dropped to about 1.5 MW at 1 second into the simulation event and rose back to about 2.3 MW at 5 seconds to simulate a cloud movement. Fig. 8 shows the responses of the system frequency (red curve), controlled branch power (green curve), PV power (black curve), and BESS power (blue curve) following cloud changes. The master plant controller detects the cloud movement and the system frequency change (with the deadband) and sends an appropriate P command to the BESS electrical control model to adjust its power output and hence regulates the system frequency and controls the MW flow on the controlled branch at the POI to be the pre-disturbance value (1.3 MW). This simulation is representative of an application where the BESS is used to smooth the output of the PV plant.

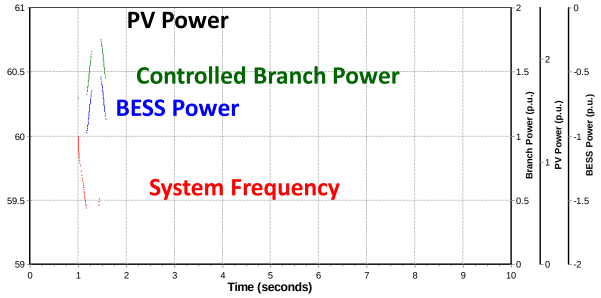

Fig. 7. System frequency (left axis), controlled branch power (right axis), PV and BESS power (right axis) outputs following the loss of a diesel generator.

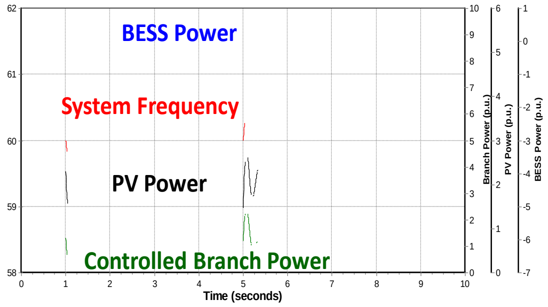

Fig. 8. System frequency (left axis), controlled branch power (right axis), PV and BESS power (right axis) output responses following cloud changes.

D. *PV Curtailment Following the Tripping of the BESS due to a Contingency Event*

In this case, a contingency event caused the tripping of the BESS and its power output dropped to zero. The PV plant is required to curtail its production to maintain the MW flow on the controlled branch at the POI to be the target value (1.3 MW). Fig. 9 shows the responses of the system frequency (red curve), controlled branch power (green curve), PV power (black curve), and BESS power (blue curve) following the tripping of the BESS. The master plant controller detects the tripping and the change in system frequency (with the deadband) and sends an appropriate P-command to the BESS electrical control model to adjust its power output and hence regulates the system frequency and controls the MW flow on the controlled branch at the POI to be the pre-disturbance value (1.3 MW).

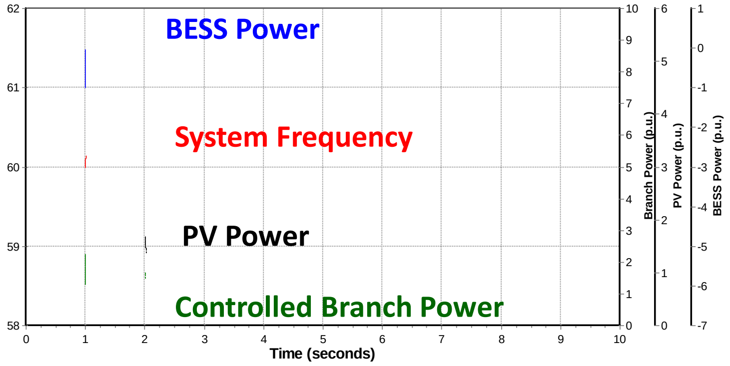

Fig. 9. System frequency (left axis), controlled branch power (right axis), PV and BESS power (right axis) output responses following the tripping of the BESS.

One of the control requirements in this case is that when the BESS on the charging mode trips due to contingency events, PV production needs to be curtailed to maintain constant net power into the grid. PV curtailment is initially based on frequency droop control. When the system frequency exceeds a threshold (e.g., 60.3 Hz) for a period of time (e.g., 1 sec), the control system sends a P-command to the PV to achieve an almost instantaneous curtailment. This advanced control logic is implemented in the auxiliary controller model as described in Section III (b) and activated in the simulation at about 2 secs as seen in Fig. 9.

V. CONCLUSIONS

This paper has presented and discussed modelling and simulation of advanced coordinated control of several DERs in a power grid with high PV penetration where PV production constitutes up to 60% of the total grid generation. The DERs, which in this case include a PV plant, a BESS, and several diesel generators, are coordinated and controlled to regulate system frequency and active power. To achieve this coordinated control objective, an auxiliary model that coordinates with the master plant controller at the system level has been designed, developed, and implemented. The master plant controller, PV, and storage controllers are modelled using a set of generic models. These generic models along with a user-developed auxiliary controller model have been configured, parametrized and tuned to maintain a power balance, to regulate system frequency, to perform curtailment, and to meet system requirements of the renewable interconnection agreement of the grid code. Dynamic simulations show that these configured and parametrized models perform as expected under system contingency events. These models are appropriate for system planning and operation studies. This paper contributes to the area of advanced DER modelling techniques for system analysis and planning with high renewable penetration.

VI. ACKNOWLEDGMENT

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APPENDIX

Fig. 10 to Fig. 13 show the block diagrams of the WECC generic models REPC_B, REGC_A, REEC_B and REEC_C for plant controller, renewable generator, solar electrical control and battery electrical control. A detailed description of these block diagrams and functionality of each of the WECC-Approved 2nd generation generic models is included in [2]-[4].

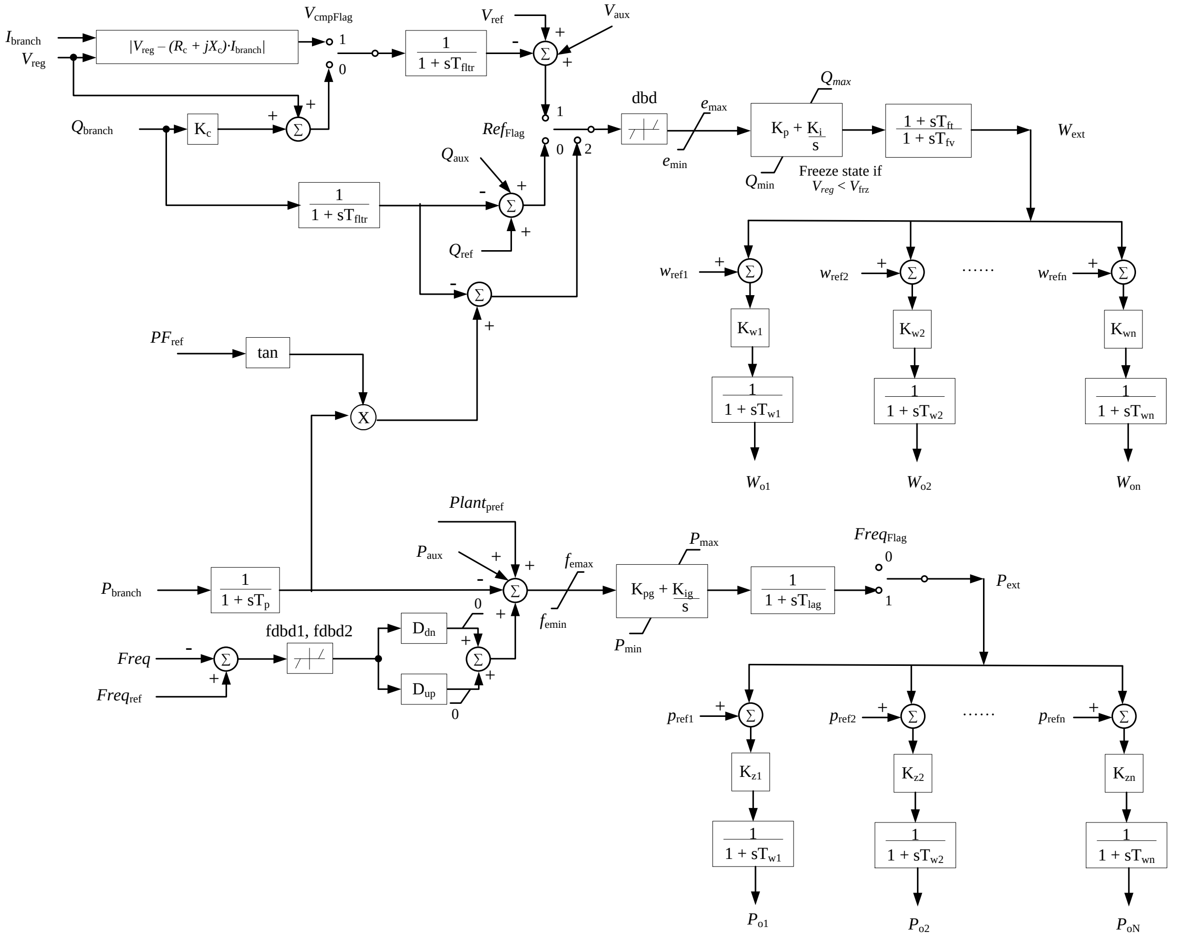

Fig. 10. Block diagram of the generic plant controller model REPC_B

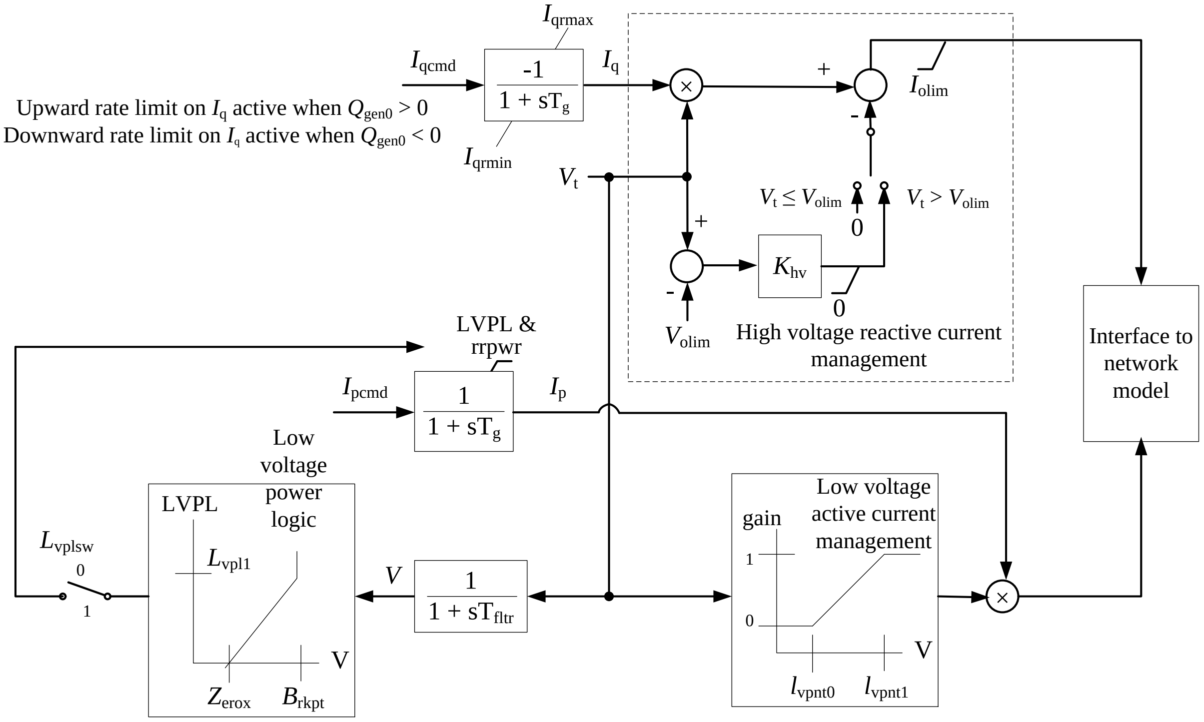

Fig. 11. Block diagram of the generic renewable generator model REGC_A.

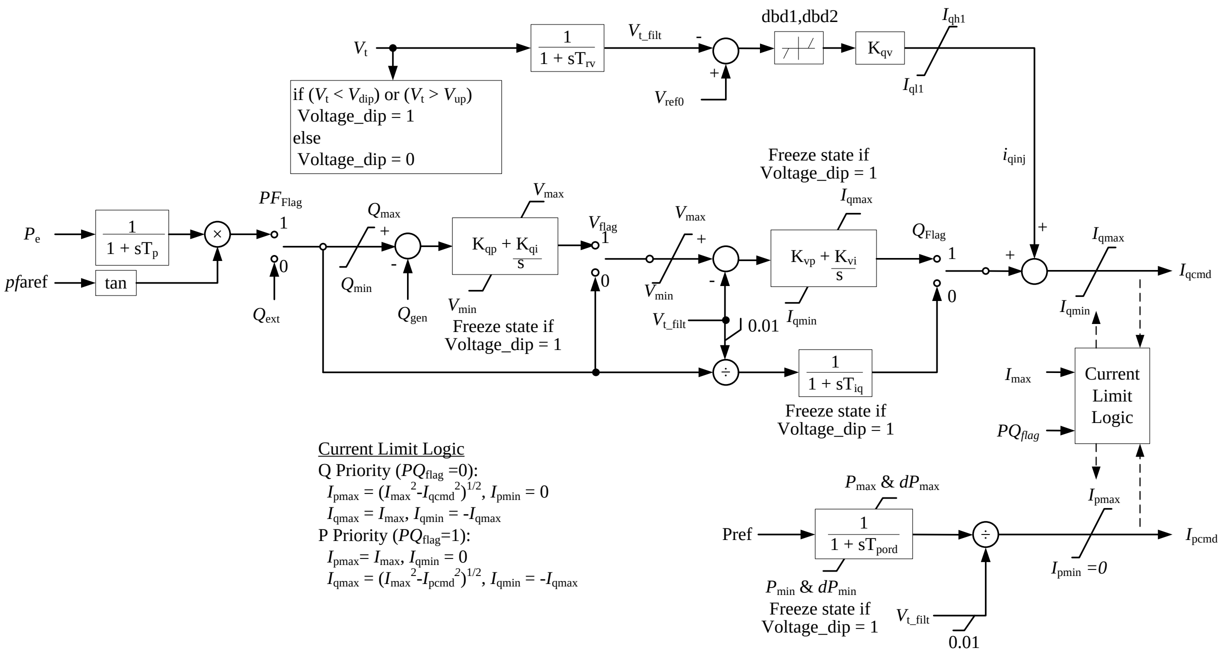

Fig. 12. Block diagram of the generic solar electrical control model REEC_B.

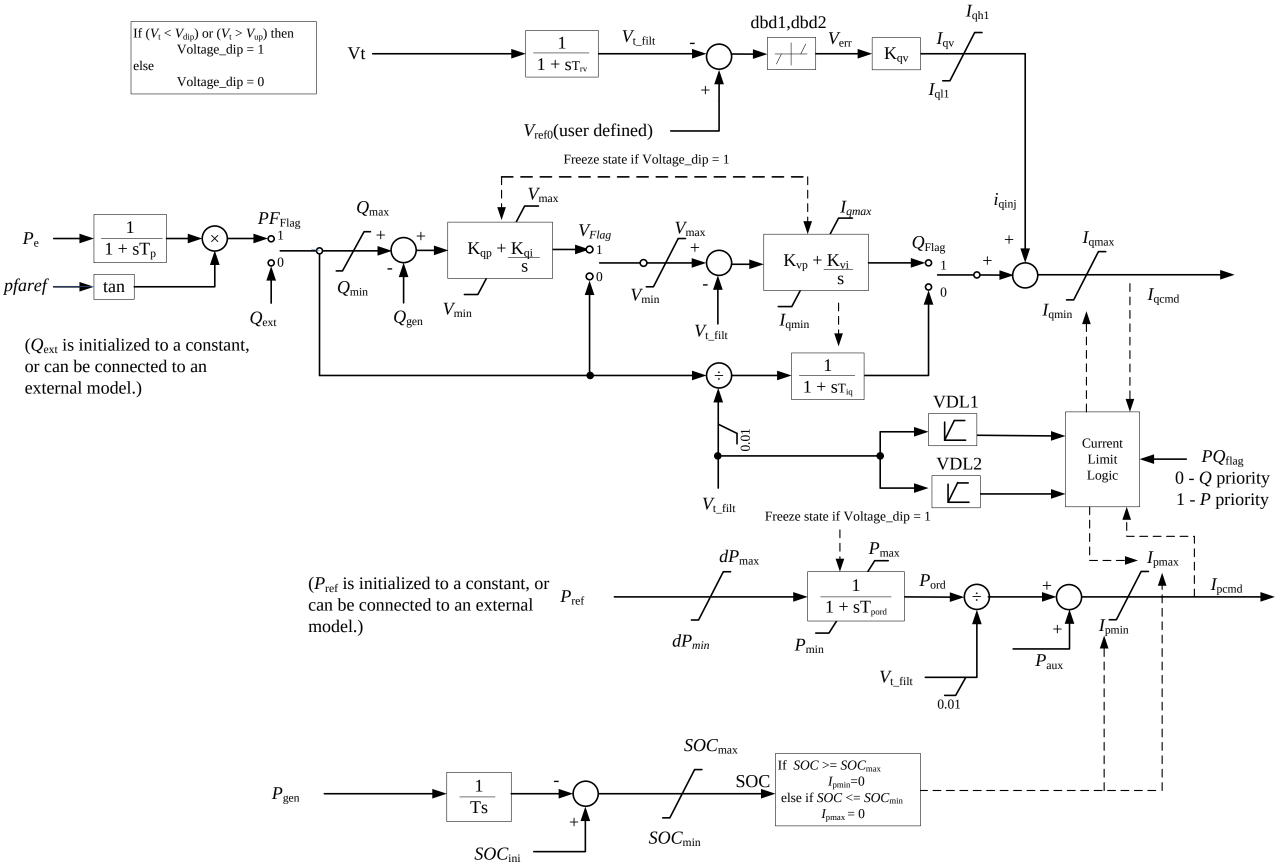

Fig. 13. Block diagram of the generic BESS electrical control model REEC_C