Power Management and Control System – Insights Into Design and Testing

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***Abstract*—The shortage and high costs of conventional fuel have diverted the concentration of major market players, specifically the Kingdom of Saudi Arabia, towards renewable energy for electric power production. However, conventional power generation and systems still play the major part. The future likely includes a mix of both conventional and renewable energy generation, demanding a proven robust, secure, and reliable power management and control system (PMCS) to integrate both generation types based on their innate behavior and limitations. A PMCS must respond to system disturbances and avoid blackouts to ensure minimum downtime. Additionally, engineers with an understanding of a PMCS can better serve power system objectives with efficient planning, optimal operation, and timely maintenance.**

Keeping in mind the future need of an intelligent PMCS for smart grid applications, this paper discusses proven design concepts and reliable hardware-in-the-loop testing via a real-time digital simulator. The paper presents various PMCS building blocks, including generation control systems (power and frequency), voltage control systems (reactive power and voltage), an islanding control system, tie-line control, high-speed generation shedding and runback, high-speed load shedding based on contingency and underfrequency, and autosynchronization systems. PMCS implementation on renewable energy sources can take a similar approach. The explanation of the PMCS components is accompanied by a brief explanation of the overall system architecture, human-machine interface (HMI), and functional testing methodology to validate the component performance and integration.

I. Introduction

A reliable source of electric power and a balanced power system network hold vital importance for industries such as refineries, oil and gas, manufacturing facilities, etc. Achieving this objective requires a robust, reliable, and adaptive system that is diligently designed and tested to keep the electric power system running and balanced in contingency scenarios. In this paper, the authors present their knowledge of designing and testing an industrial grade power management and control system (PMCS) based on years of experience. The paper has been designed to cover all major aspects of a PMCS by presenting basic concepts, design, and testing philosophies.

Section II presents an overview of a PMCS. The design concepts are explained in Section III. Section IV provides brief overview of the PMCS human-machine interface (HMI). Section V presents testing details from various aspects. Section VI briefly discusses a PMCS for renewable energy sources.

II. PMCS Functionality Overview

A PMCS is ideal for industries with onsite generation and/or that are grid connected. It contains automated control functions specifically designed to prevent, detect, and mitigate system blackouts in grid-connected or islanded mode. Automated functions within a PMCS control major power system assets for optimal economic operation. By properly collecting, processing, and presenting power system data as usable information, the PMCS system enables operators, maintenance personnel, and engineering staff to diagnose system events, predict equipment failures, and minimize unnecessary maintenance.

III. Power Management and Control System Design

A. Engineering Inputs and Documentation

The design process requires a complete package of engineering design documents, some of the key documents are briefly highlighted as follows, all these documents are also provided to customer for their better understanding of PMCS design basis:

1) Simplified Single-Line Diagram

A simplified single-line diagram (SSLD) is developed based on the customer SSLDs and selection of substations and/or portions of substations. The electrical assets are arranged as per positive power flow in order of utility substation, utility lines, interface substation, generation substations, intermediate substations, and emergency substations and loads. The SSLD provides a picture of the overall power system and assists with topology tracking and a power system model for testing. Fig. 1 shows an example SSLD.

2) Data Flow Diagram

This document is designed to identify communication protocols and data transmission hierarchy among various devices of PMCS.

3) Input/Output List

This paper provides a complete list of all hardwired and soft I/O with complete substation, building, panel, intelligent electronic device (IED), and signal address identification-based applicable protocol.

4) Functional Design Specification

This paper provides the complete design philosophy of a PMCS including different control algorithms selected as per customer specification. The paper also provides the PMCS interface details for power system assets including generators, transformers, circuit breakers, disconnect switches, and any applicable process control system.

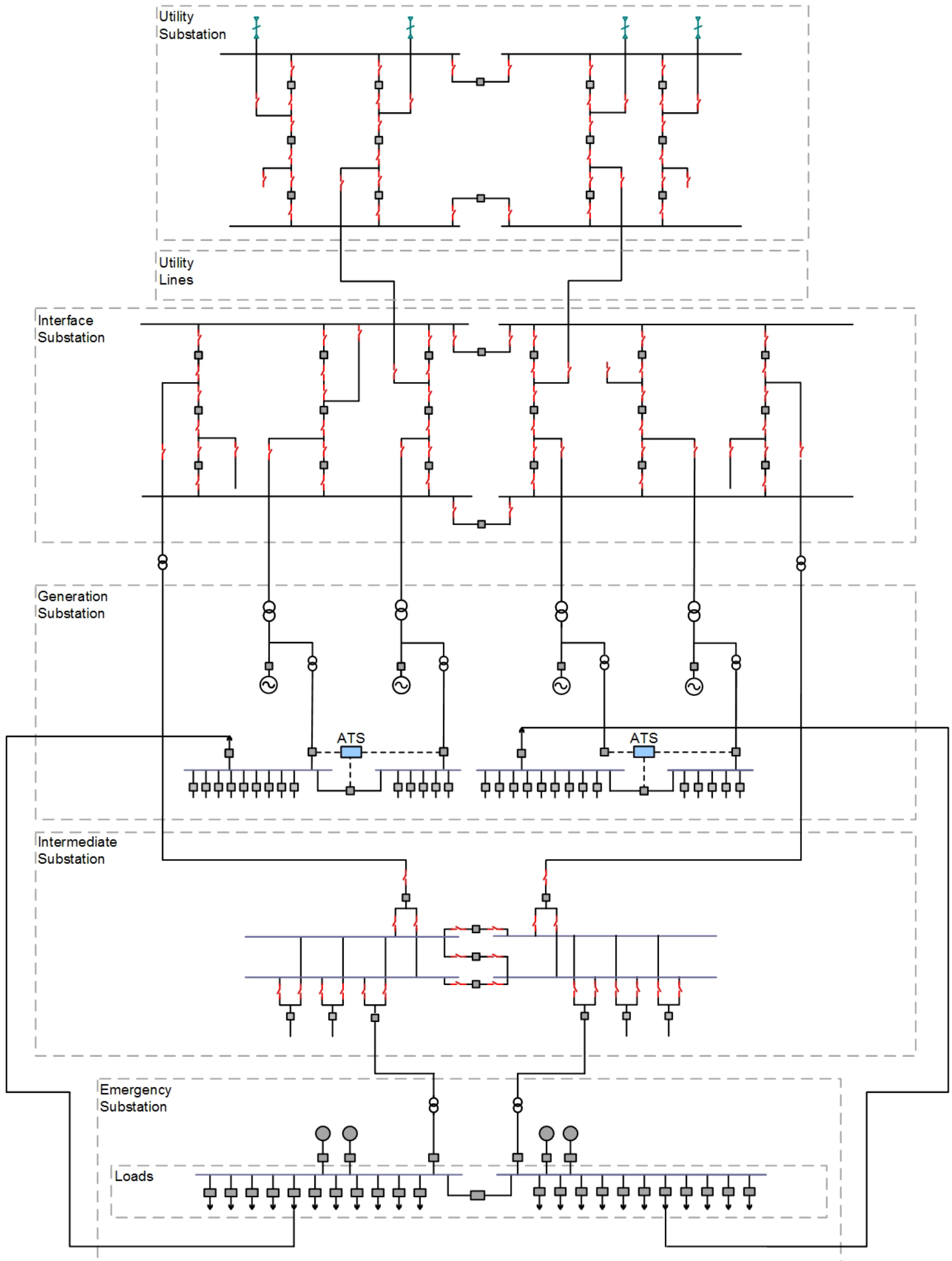

Fig. 1. Example of Simplified Single-Line Diagram

B. System Architecture

A PMCS consists of dedicated logic controllers that provide the core functions and IEDs that provide metering and status data. IEDs are responsible for gathering various status, e.g., breaker, and disconnect information, and power system metering values. Data concentrators (DCONs) are deployed to accumulate the data from field devices and send them to PMCS controllers for analysis and decision making. Controllers perform logical operations at high speed and low speed based on the control algorithm and send control signals to the DCON where they are routed to a specific IED. Controllers also communicate with HMI software. The preferred protocol for communication between DCONs and an IED is IEC 61850-based GOOSE (high speed) and Manufacturing Message Specification (MMS) (slow speed), however, a PMCS can also include IEDs supporting DNP3 or Modbus®. Fig. 2 shows the simplified system architecture for a PMCS.

C. Slow-Speed Control Functions

In a PMCS, slow-speed controls correct different power system parameters including voltage, frequency, power flows, and power factor, as well as participate in system synchronization by controlling governor and exciter of selected generators. Collectively, it can be called a generation control system (GCS), however, it is comprised of various control algorithms.

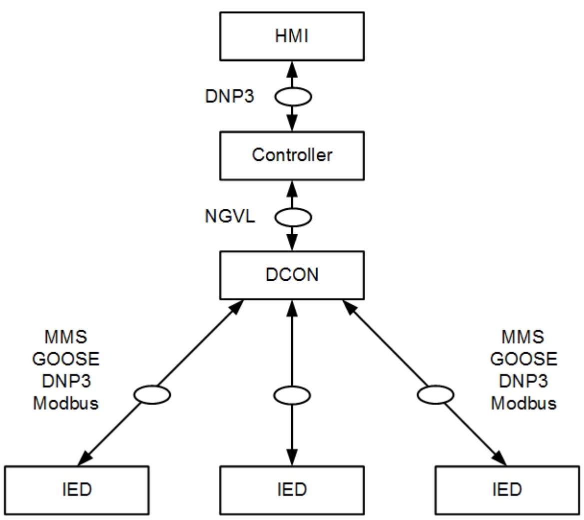

Fig. 2. PMCS System Architecture with Data Flow Paths

1) Automatic Generation Control System

The automatic generation control (AGC) system dispatches turbine generator governor set points for equal load sharing while simultaneously controlling the system frequency (F) and power (MW) flow across tie lines.

The AGC algorithm is presented in Fig. 3. The AGC system sends a speed or MW set point to the governors of running turbine generators. The set point for each generator is determined by the optimal load-sharing controller that receives biased commands from either the frequency or tie-flow controller loops; the island detection logic determines which of these loops is activated.

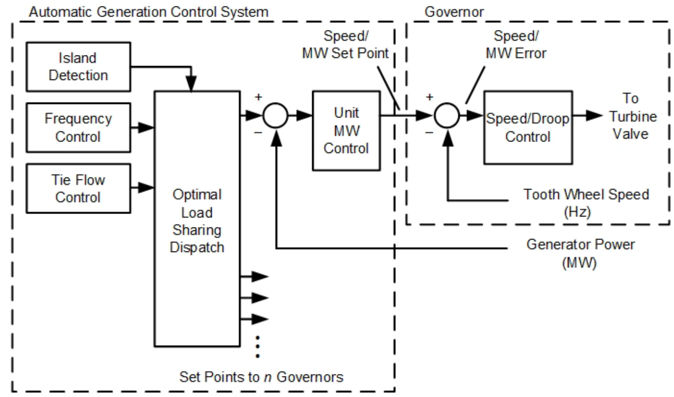

Fig. 3. Typical AGC Control Strategy

2) Voltage Control System

The voltage control (VC) system dispatches turbine generator exciters for equal percentage reactive load sharing while maintaining the voltage through generator excitation and controlling the onload tap changer (OLTC), if applicable. The VC system monitors the generator terminal voltages to stay within acceptable limits. It can also dispatch specific power factor (PF) or reactive power (MVAR) output from individual generators or across the utility breaker based on user selection. The VC system is also integrated into the autosynchronization system (AS). Fig. 4 shows the overall strategy of the VC system algorithm.

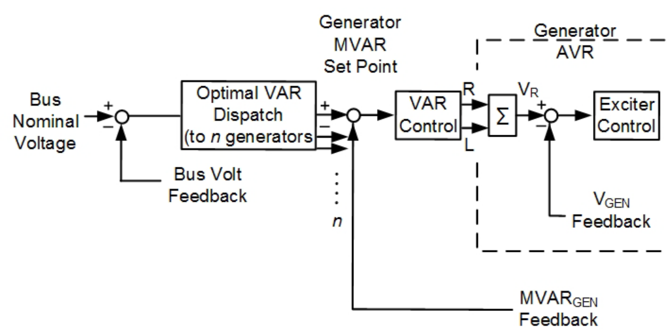

Fig. 4. Typical VCS Control Strategy

3) Islanding Control System

The islanding control (IC) system controls the modes of the governors and exciters. The control mode for the governor can be either droop or isochronous based on plant operating conditions and user selection. The control mode for the exciter can be VOLT, PF, or VAR based on the operating scenario and user selection. The IC system tracks the number of islands in the system and generators connected to those islands. Accordingly, it creates the individual AGC system and VC system control loop for each island formed.

4) Generator Capability Tracking System

An intelligent GCS is equipped with a generator capability tracking algorithm that uses a least-value method to determine the allowable operational region for the AGC and VCS controllers. The controllers will dispatch a generator within user-defined machine regulation limits. This region is used to calculate the MW and MVAR spinning reserves for each unit. Fig. 5 represents generic capability curves and shows different operating scenarios within the allowable operational region (indicated in red). Fig. 5 (top) shows an example in which the user-entered regulation limits are within the capability curve; however, they are outside the turbine limit and vice versa for Fig. 5 (bottom).

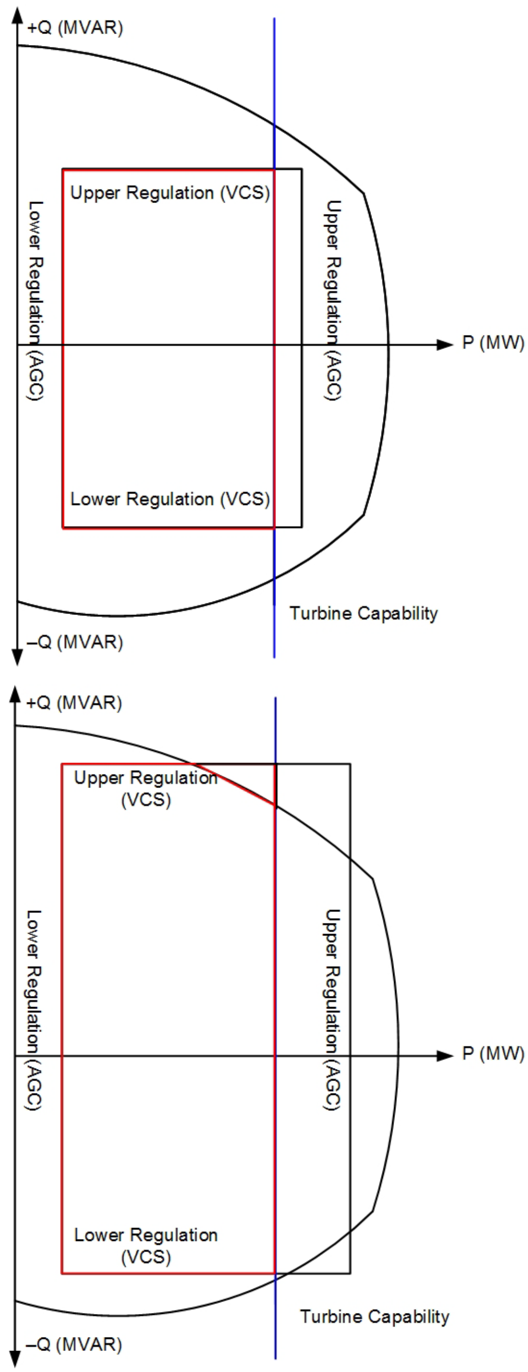

Fig. 5. Generator Capability – Regulation Limits With Generator Boundary

5) *Miscellaneous Controls*

In addition to the major control algorithms, a PMCS may consist of other controls. One additional control is economic generation dispatch. In this case, AGC set points will also depend on the fuel cost parameters. Another control is asset management-based generation dispatch. In this case, the AGC setpoint calculation is also a function of different turbine modes based on air/fuel ratios and nozzle firing scheme. Selecting the appropriate mode and MW set points directly impacts the life and maintenance cycle of the turbine.

6) *Autosynchronization System*

An AS system is required for the generators, tie lines, and bus couplers. Unit synchronization systems synchronize individual generators to power grids while island synchronization systems are synchronized and reconnect power system islands. These systems are required to function automatically with minimal human supervision because they must dispatch multiple generators simultaneously to reduce slip and voltage differences at the interconnection point [3]. Once the autosynchronization process is initiated, the AS system performs safe, secure, unattended synchronization control of islanded power systems.

The AS system algorithm is presented in Fig. 6; the slip and voltage difference measurement from the AS IED is fed to the GCS. The GCS dispatches governors and exciters to bring the frequency and voltage differences within breaker closing limits. The AS IED automatically closes the breaker once the phase angle is within the defined band.

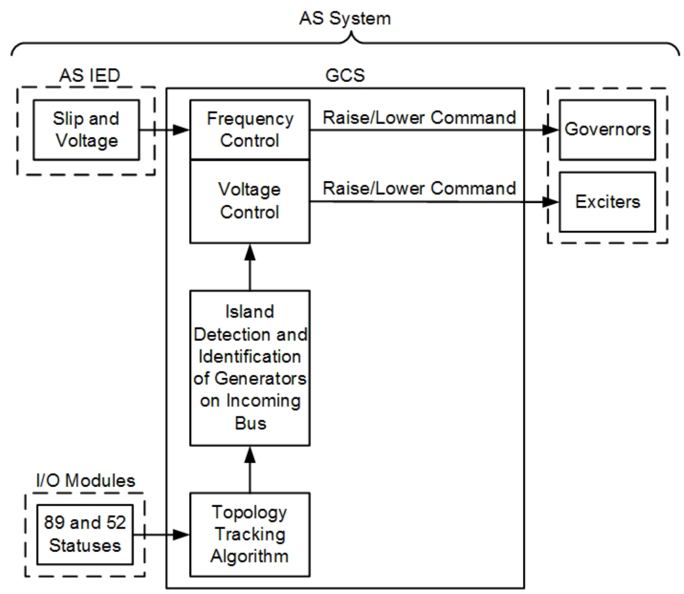

Fig. 6. Autosynchronization Control System

D. *High-Speed Shedding Control Functions*

High-speed shedding control functions are required to mitigate power system imbalance and prevent blackout. These fast-acting control functions maintain balance between mechanical power input and electric power consumption by tripping generator and/or load breakers based on a triggered condition, i.e., excess generation or excess load.

1) *Contingency Load-Shedding System*

A contingency-based load-shedding (CLS) algorithm sheds load to maintain the power system balance by reducing the total plant electrical load to less than the calculated available turbine and generator capacity after a contingency occurs. Because of the power system net rotating inertia, the CLS system operates fast enough such that loads are shed prior to any significant frequency decay.

When a contingency breaker opens, the CLS controller determines the loads to shed based on the contingency status and metering, user-settable load-shedding priorities, user-settable incremental reserve margin (IRM) values, topology status, load status, and metering. The CLS controller sends the load trip signals to respective IEDs, the output contacts of which are wired to trip coils of breakers. Fig. 7 explains the CLS algorithm.

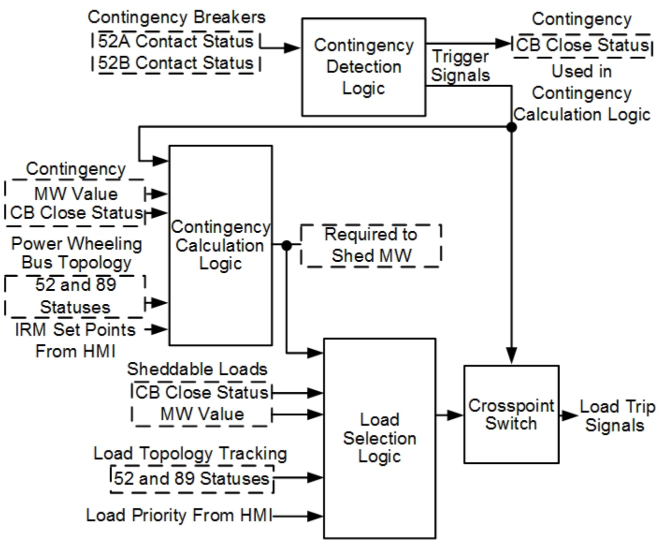

Fig. 7. CLS System Algorithm

2) Underfrequency Load-Shedding System

It is a fast load-shedding algorithm that maintain the power system balance by reducing the total plant load by fixed amounts of load power at two separate underfrequency (UF) levels. The UF level detection occurs in relays located at each bus/generator. The underfrequency load-shedding (UFLS) system acts as a backup to the CLS system.

When the IED detects a UF event, it sends a high-speed signal to the UFLS system. The UFLS controller determines the load to shed based on the UF trip level, user-settable load-shedding priorities, topology status, load status, and metering. The UFLS system sends the load trip signals to IED; output contacts of which are wired to trip coils of breakers. Fig. 8 explains UFLS algorithm.

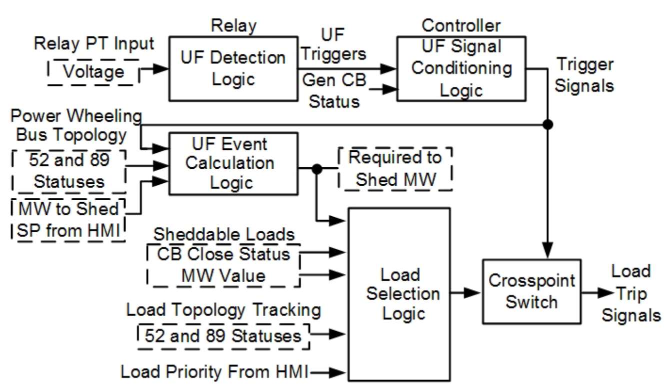

Fig. 8. UFLS System Algorithm

3) High-Speed Generation Shedding and Runback Control

An event resulting in excess generation usually occurs when a tie-line or bus coupler breaker opens under load, which requires generation reduction for balancing the power system. The generation-shedding (GS) system is a fast, contingency-based algorithm that sheds and runs back generators to maintain the power balance after a contingency occurs by reducing the total island generation and making it approximately equal to the running load of the island. Because of the power system net rotating inertia, the GS system operates fast enough that generation sheds prior to any significant overshoot in frequency.

When a contingency breaker opens, the GS system controller determines the generation to shed or run back based on the contingency status and metering, user-settable generation-shedding/-runback priorities, topology status, generator status, and metering. In the case of a shedding decision, the GS system sends generator trip signals to an IED, the output contacts of which are wired to trip coils of generator breaker. And, in case of run back decision an analog MW set point is routed to the turbine generator controller via an IED to reduce generator output.

4) Overfrequency Generation-Shedding System

The overfrequency generation-shedding (OFGS) system algorithm sheds generation to maintain the power balance by reducing the total generation by fixed amounts at two separate overfrequency (OF) levels. The OF level detection occurs in relays located at each generator. The OFGS system acts as a backup to the GS and runback.

When the relay detects an OF event, it sends a high-speed signal to the OFGS system controller. The OFGS system algorithm in the controller determines the generators to shed based on the OF trip level, user-settable generator-shedding priorities, topology status, generator status, and metering. The OFGS system sends the generator trip signals to the IED; the output contacts are wired to the generator breaker trip coils. Fig. 9 explains the OFGS system algorithm.

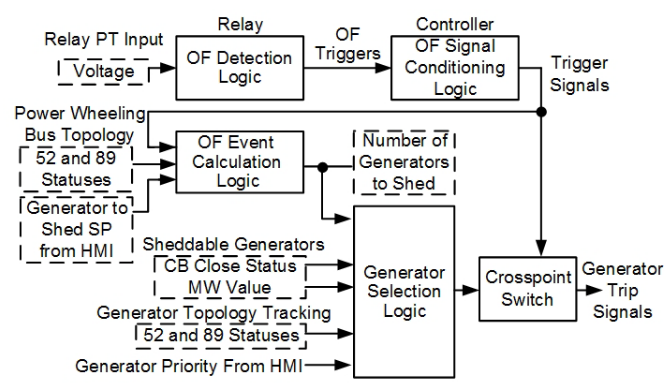

Fig. 9. OFGS System Algorithm

E. Emergency Black Start System

Upon occurrence of blackout, a PMCS aids to restart the power system via the emergency black start (EBS) system. This system activates as soon as a blackout is detected. It begins with starting available emergency diesel generators followed by restoring identified critical loads based on user-settable load restoration priorities. Once the load restoration is complete, the EBS system helps the operator restore normal power supply (usually from gas/steam turbine-driven generators) by closing required circuit breakers eventually leading to synchronizing normal power and power from emergency diesel generators (EDGs). When the EDGs and normal power source are synchronized, load is smoothly transferred from the EDGs to the normal power source. When all EDGs are off loaded, the PMCS sends a switch-off command to all EDGs. The PMCS HMI will show the system state and allow the operator to sequentially execute each step of the EBS process.

IV. PMCS Human-Machine Interface

The HMI serves as an interface between the power system operator and PMCS controller. The PMCS HMI is customized as per specific project requirements and applicable PMCS control algorithms. The HMI provides user operability to issue commands and enter set points for power system parameters. In addition, the PMCS HMI provides power system visualization and high-speed control algorithm prediction, i.e., CLS, UFLS, GSS runback, and OFGS actions for identified contingencies.

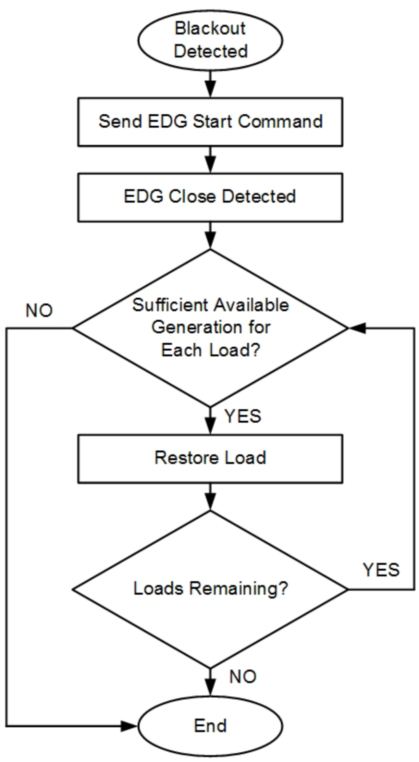

Fig. 10. EBS System Logic Flow

V. PMCS Integrated Testing Via Hardware-in-Loop Using Real-Time Digital Simulator

A. Power System Modeling

The model developed for the real-time digital simulator (RTDS) testing represents the complete system according to the single-line diagram(s) along with modeling different power system components (generators, transformers, transmission lines, distribution lines/cables, and loads) details of those are gathered from manufacturer.

B. Testing Setup

The PMCS testing setup is divided into two major parts RTDS setup and static simulator. Table I lists these components.

1) RTDS Arrangement

The RTDS setup provides real-time representation of the actual power system. It is integrated with actual field controllers to test and study real-time dynamic system response. All possible logic programmed in the PMCS controller can be tested and verified via RTDS testing. The results characterize various system parameters to achieve the required system response.

2) Static Simulator

The static simulator replicates the field devices used for required data collection and commands transmitting. It serves to understand system steady-state response for high-speed shedding algorithms and can be used as a training simulator for power system operators to test actions of high-speed shedding functions under different system configuration.

Table I
Major Components of PMCS Testing Setup

Component	Purpose
CONTROLLER	Configured with specific control logics based on selected PMCS algorithms.
DCON	Configured as an interface between controllers and simulation HMI.
SIMULATION HMI	Used to set and modify various operational parameters and scenarios.
PMCS HMI/RTDS RUNTIME	Actual PMCS GUI used by system operators to interact with PMCS via sending commands/set points and monitoring.

C. Testing Objectives

Integrated hardware-in-loop testing validates PMCS programmed logic functionality. Following objectives are required to achieve from this testing:

- RTDS model verification and validation with manufacturer-conducted lab and field tests.
- Suggested incremental generator reserve margins for the primary load-shedding scheme.
- Identification of correct frequency set points for the underfrequency scheme, if applicable.
- Identification of system scenarios for testing based on both developer experience and customer operational requirement.
- Successful operation of PMCS control logic for all preidentified scenarios.

D. Closed-Loop Simulations

PMCS designers and power system operation experts identify base case scenarios for different operating conditions (nominal, light, and peak loading) to validate PMCS performance in all conditions. Single and multiple contingencies are forcibly triggered to analyze system behavior and observe corrective actions taken by PMCS high-speed control algorithms; this brings power system parameters within a healthy operating range and allows the PMCS slow-speed control to bring them back to nominal. Fig. 11 depicts a power system running as one island and then separating into two islands.

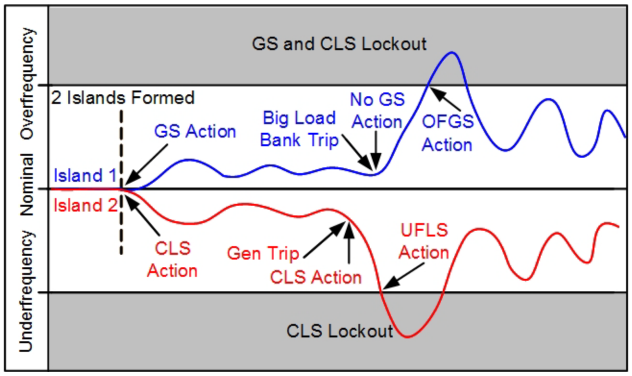

Fig. 11 Example Simulation Result

The respective PMCS algorithms respond to this separation as follows:

1. The excess generation on Island 1 is countered via the decremental reserve margin (DRM) settings on the PMCS HMI that allow the governors to naturally decrease their power outputs using their negative power reserves.
2. The excess load on Island 2 is countered via IRM settings on the PMCS HMI that allows the governors to naturally increase their power outputs using their power reserves.
3. All governors are set in droop mode; therefore, the frequency of both islands settles at a new frequency value that is slightly higher than nominal in Island 1 and lower than nominal in Island 2.
4. A generator trips in Island 2 and the CLS system sheds load. The CLS load shedding was insufficient to match the lost generation.
5. Insufficient CLS on Island 2 causes a frequency decay that crosses into the first underfrequency load-shedding level. Subsequently, the UFLS system makes a load-shedding decision and locks out the CLS system from further action on Island 2.
6. In Island 1, a large load bank trips and the island exhibits a frequency rise because of excess generation. GS and runback do not react as the breaker of a large load bank is not considered a contingency. However, the rise in frequency causes the OFGS system to shed generation at the first overfrequency generator-shedding level. This locks out the CLS system from further action on Island 1.
7. The UFLS and OFGS systems arrest frequency deviations and allow the AGC to bring the frequency closer to nominal.

VI. PMCS With Renewable Energy Sources

A smart PMCS can interact with both conventional and renewable energy sources. The work presented in [1] demonstrates an example of controlling conventional and renewable energy sources via PMCS. The paper [1] considers the case of a power system with a mix of diesel and gas turbine (GT), photovoltaic (PV), and battery energy storage system (BESS) generators. The diesel and GT generators are controlled for load sharing and maintain operating margins to neutralize any prospective system disturbance. The real power set point for the PVs is set to maximize the PV power output. The real power set point for the BESS asset is normally maintained at zero and only changed via PMCS control to counter frequency deviations (usually applicable when islanded from utility). If islanded from utility, the PMCS biases the operation of the diesel and GTs to maintain islanded system frequency at the set point and drive the BESS power output to zero (if possible).

The reactive power set points for both conventional and renewable energy sources are dispatched to ensure equal percentage sharing based on asset capability limits. In turn, both types of generation sources dispatch reactive power to maintain the power factor control at the utility interconnection. When the system is islanded and the utility tie breakers are open, these same assets are equally dispatched to an MVAR output while maintaining system bus voltages.

VII. Conclusion

Deploying a robust, rugged, secure, efficient, and reliable PMCS requires understanding of important aspects identified and explained in this paper that are applicable to conventional generation and renewable energy sources. A PMCS based on predefined control algorithms, efficient communications architecture, appropriate protocols, diligently developed real-time power system model, and critical scenario-based integrated real-time testing is key to deploying an efficient platform for electric power system operation and control in a smart grid environment.

VIII. References

[1] S. Manson, B. Nayak, and W. Allen, "Robust Microgrid Control System for Seamless Transition Between Grid-Tied and Island Operating Modes," proceedings of the 44th Annual Western Protective Relay Conference Spokane, WA, October 2017.

[2] S. Manson, A. Upreti, and M. Thompson, "Case Study: Smart Automatic Synchronization in Islanded Power Systems," proceedings of the 51st Annual Industrial & Commercial Power Systems Technical Conference, Calgary, AB, May 2015.

[3] K. G. Ravikumar, T. Alghamdi, J. Bugshan, S. Manson, and S. K. Raghupathula, "Complete Power Management System for an Industrial Refinery," in *IEEE Transactions on Industry Applications*, Vol. 52, Issue 4, July–August 2016, pp. 3565–3573.

IX. Biographies

Maaz Kazmi is a special protection systems engineer. He joined Schweitzer Engineering Laboratories, Inc. in 2011. He earned his B.E. degree from NED University of Engineering and Technology in Karachi, Pakistan. Before joining SEL, he was senior executive engineer in the Energy and Automation Unit of Siemens Pakistan Engineering Co. Ltd. He has over thirteen years of experience in design, development, testing, commissioning, technical documentation, and customer training in the areas of power management solutions, substation automation, and HMI development. He has also acquired extensive knowledge in generation control systems for industries and utilities, utility system operations, and remedial action schemes.

G. M. Asim Akhtar is a special protection systems engineer. He joined Schweitzer Engineering Laboratories, Inc. in 2015. He earned his B.E. degree from NED University of Engineering and Technology in Karachi, Pakistan, and his M.Sc. degree from King Fahd University of Petroleum and Minerals in Dhahran, Saudi Arabia. Before joining SEL, he was employed by Pakistan Petroleum Limited as a senior engineer responsible for electric power operations and maintenance. His research interests include power management systems, substation automation, electric vehicles, and the integration of renewables into power grids. In addition to his technical papers in the field of electricity market and electric vehicles, he holds one U.S. patent.

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