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Advanced Stability Analysis of Grid-Connected Hybrid Renewable Energy Systems Incorporating Solar PV and Wind Energy Conversion Systems (WECS)

(Case Study: Indore Water Supply Project, Indore Municipal Corporation, Madhya Pradesh, India)

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Abstract - This paper introduces an enhanced stability-analysis of a grid-interconnected hybrid renewable energy system (HRES) with solar PV/WECS for the Indore Water Supply Project of IMC, Madhya Pradesh (India). The Indore Water Supply Project case-study builds on the submitted DPR/press kit and hydraulic-report material. These project documents describe an extensive multi-stage municipal water- supply scheme including intake works, raw-water-pumping, 400 MLD water treatment plant, pure-water-pumping, booster-pumping station, pumping-main, bulk-water distribution and SCADA infrastructure.

The DPR reports that the current urban water supply is about 436 MLD at 147 LPCD, covering a population of about 29.39 lacs and that intermittent coverage with a low rate of non-revenue water should be converted to a continuous water supply scheme with high coverage.

The proposed Phase-I works include Narmada basin intake station (1650 MLD), 18 raw-water-pumping units, 400 MLD WTP, 6 pure-water-pumping units at WTP, electrical sub-station, SCADA, 132 kV transmission line and 132 kV sub-station. For these pumping-dominated loads, PV-WECS-grid architectures are designed, while steady-state, voltage, small-signal, transient and power quality stability are modeled and studied. Because the given project documents lack a solar-resource dataset, a wind-resource dataset and the dynamic inverter data, HRES capacities and stability outcomes are kept as modeling variables.

Keywords: Hybrid renewable energy system; Solar PV; Wind energy conversion system; Grid-connected HRES; Water-supply pumping; Voltage stability; Small-signal stability; Transient stability; SCADA; Indore; AMRUT 2.0.

INTRODUCTION

Pumping in municipal water-supply systems is responsible for large electrical-energy loads as the abstraction, treatment, transmission and distribution of water is powered by the continuously running pump-motors. Energy loads can be aided with clean-re electricity by hosting renewables on the system, but they cause power-electronic interactions – voltage, frequency, harmonics and dynamic-control interactions. The

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Indore Water Supply Project is used here as a large system for studying system interactions.

Filециteturn 8 file 9 L749-L756 DPR states the current water-supply amount is 436 MLD, the supply rate is about 147 LPCD and the network caters 29.39 lakhs people.

1.The filedciteturn8file9L680-L845 current supply is intermittent, the water supply is for a duration of 45 minutes-1 hour on alternate days and IMC plans to move towards a continuous water supply, while reducing NRW and improved service-level performance. Fileciteturn 8 file 9 L749-L756 The stated current water supply mode is intermittent and same as above, which means provision of water for a duration of 45 minutes to 1 hour on alternate days. The proposed research considers the water supply as an energy-water nexus. The aim is not to determine the annual renewable energy generation alone but examine how PV and WECS can be tied to the electrical infrastructure in a way that does not affect pump reliability, voltage quality and the stability of the system.

2.CASE STUDY: INDORE WATER SUPPLY PROJECT

The DPR submitted by you is for Indore Municipal Corporation. Your project comprises large intake, treatment, pumping, transmission and distribution elements. The urgent-priority Phase-I package proposes 1650 MLD Narmada intake, 18 raw-water pumping units, a 400 MLD WTP, six pure-water pumping units at the WTP, sub-stations, SCADA, 132 kv line and a 132 kv sub-station at Bhakali. Fileciteturn 9 file 4 L249-L29

Parameter	Documented project value
Urban authority	Indore Municipal Corporation (IMC)
Present water supply	~436 MLD
Present supply rate	147 LPCD
Population served	~29.39 lakh
Present supply pattern	Intermittent; ~45 min–1 h on alternate days
Proposed intake	1650 MLD, Narmada River
Proposed WTP	400 MLD
Raw-water pumping machinery	18 units
Pure-water pumps at WTP	6 units
WTP-to-Booster Station pumping main	400 MLD; 5980 m; 155.45 m head
Booster Station-to-proposed BPT	580 MLD; 1050 m; 278 m head
Electrical transmission	132 kV line, 38 km in Phase-I summary
132 kV substation	Bhakali
SCADA	At 400 MLD WTP and Booster Station

Section 15-2 The DPR 22 further states that the raw-water pumping main was designed for an intermediate demand of 400 MLD and a design capacity of 412 MLD after considering transmission loss. The raw-water pumping main shown in the site document has a length of 14,950 m, and static-head/ design data is available for the piping in the hydraulic design. Fileciteturn9file6L381-L432

3. WATER-SUPPLY SYSTEM AS AN ELECTRICAL LOAD

It is therefore evident that the project's energy requirements will be significantly influenced by the operation of pumping and treatment facilities. Further, the pumping equipment, motors, electrical infrastructure, substations, transformers, SCADA and instrumentation is identified by the project documentation as being the key operation and maintenance assets. Fileciteturn9file1L97-L139 The hydraulic design defines the total raw-water and pure-water pumping requirements at the maximum flow and head conditions.

The raw-water and WTP to Booster Station sections are designed for 412 MLD at 155.45 m head and 400 MLD at 155.45 m head respectively, while the final booster to BPT section is designed for 580 MLD at 278 m head.

FILECITETURN9FILE6L381-L396 FROM THESE OPERATING POINTS, IT IS CLEAR THAT THE PRIME ELECTRICAL LOADS FOR RENEWABLE INTEGRATION WILL CONSIST OF PUMP MOTORS AND ASSOCIATED SUBSTATIONS, SO THE FINAL ELECTRICAL MODEL SHOULD REFLECT THE RATED EFFICIENCIES, STARTING METHOD AND TRANSFORMER IMPEDANCE OF THE APPROVED MOTOR MODEL, AND FEEDER CHARACTERISTICS BASED ON THE LATEST ELECTRICAL DESIGN INSTEAD OF INFERRING MISSING DATA FROM THE HYDRAULIC INFORMATION ALONE.

4. PROPOSED PV-WECS-GRID ARCHITECTURE

The suggested system configuration includes the utility grid, the project electrical grid, renewable generation, WECS, power-electronic converter, Supervisory Energy-management System (EMS) The renewable turbines are interconnected at certain buses of the electrical network close to key water pumping loads, using certain network voltage, short-circuit and protection constraints.

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Component	Proposed research role	Main stability concern
Utility grid	Balancing and reference source	Voltage/frequency and grid strength
Solar PV array	Daytime renewable generation	Intermittency and DC-link dynamics
PV inverter	Grid interface and reactive support	PLL/current-control interaction
WECS	Wind-energy generation	Generator and converter dynamics
WECS converter	Grid interface	Torque, current and DC-link control
Pump motors	Major electromechanical loads	Starting current and voltage dip
Substations/transformers	Power transfer to pumps	Thermal/loading and voltage stability
SCADA/EMS	Monitoring and coordinated dispatch	Measurement/communication delays

5. RESEARCH OBJECTIVES

The primary goal of this system is to find the operational parameters and limits of integrating PV and WECS into Indore water-supply electrical system. The specific goals of this system are to evaluate the range of renewable penetration achievable, ascertain voltage response at the pump buses, analyze small-signal modes brought about by the converter controls and the motor loads, gauge the transient response during faults and start-up of the pumps, and develop an EMS that optimizes the coordination of renewable with the pumping task.

6. MATHEMATICAL FORMULATION

At the point of common coupling, the active-power balance is:Pgrid(t) = Pload(t) PPV(t) PW(t) + P_loss(t) And, the reactive-power balance is:

Qgrid(t) = Qload(t) QPV(t) QW(t) + Qloss(t) Rre=% (PPV + PW)/Pload Renewable penetration, defined as RRE, is calculated as RRE = (PPV+ PW) / Pload 100%. The annual grid-energy reduction can be written as E = 1 Egrid, HRES/E_grid, base. Nonlinear dynamic model of small-signal stability is linearized about an operating point x=Ax+Bu. The eigenvalues of A are the_ i. For an oscillatory eigenvalue =j, the modal damping ratio (or power system damping ratio) is = / (+). For pumping loads, hydraulic power is given as Ph=gQH and electrical input power as Pe=gQH/(pm) with the actual approved pump and motor. This defines the coupling between the hydraulic model and the electrical HRES model.

7. STABILITY-ANALYSIS METHODOLOGY

7.1 Steady-State Power Flow

Initial stage is to determine a validated grid-only operating point on the approved electrical single-line diagram, transformer data, load center and feeder impedances and pump loads. Increase PV and WECS until maximum capacity. Bus voltage, current in feeders, transformer loading, reactive-power exchange at PCC and import from the grid are monitored.

7.2 Voltage Stability

Voltage stability is evaluated at intake, WTP, Booster Station and other big pump buses. They are maximum bus voltage, maximum deviation of bus voltage, reactive power reserve and reactive power recovery time after disturbance.

7.3 Small-Signal Stability

The time domain model shall comprise PV inverter PLL, current controller, DC-link controller, active-power controller and Volt/VAR control as well as the WECS generator/converter control system. Eigen value analysis shall be applied to identify modes with poor damping and participation factors to identify dominant states.

7.4 Transient Stability

Simulate three-phase faults, voltage sags, PV transient reduction, wind ramps, renewable trips, pump starting events. Critical output: PCC voltage, frequency deviation, converter current, DC-link voltage, active-power recovery and settling time.

7.5 Power Quality

PCC harmonic distortion, voltage unbalance, power factor and reactive-power fluctuations should be evaluated because the network combines converter-based renewable sources with large motor-driven pumping loads.

8. PROPOSED SIMULATION SCENARIOS

Case	Configuration	Purpose
S0	Grid + existing/projected pumping load	Validated reference case
S1	Grid + Solar PV	PV-grid stability
S2	Grid + WECS	WECS-grid stability
S3	Grid + PV + WECS	Hybrid interaction
S4	Hybrid + Volt/VAR control	Voltage support
S5	Hybrid + EMS	Coordinated renewable/pump operation
S6	Hybrid under pump starting	Motor-converter interaction
S7	Hybrid under grid fault	Transient stability and ride-through
S8	Hybrid under renewable ramps	Intermittency robustness

The project DPR does not define a solar-PV capacity, WECS capacity, site wind-speed distribution, inverter control settings, or renewable-resource time-series. These parameters should be acquired through a separate renewable-resource and electrical study prior to claiming numerical simulation results.

9. ENERGY MANAGEMENT STRATEGY

The EMS should give highest priority to maintaining the water supply, then maximum electrical limits and finally the use of renewable energy. During periods of high solar production, PV generation should be used to replace pumping power. Wind generation should be used to replace PV production during

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non-solar times when wind is available. The grid remains the balancing source.

The significantly large water-storage and pumping system offers the potential for operational flexibility, whereby the EMS can, within hydraulic limits, schedule pumping to better use the renewable sources of power. This should be checked against the hydraulic model and not just assumed. The DPR strongly encourages use of hydraulic modeling in the reliable and efficient operation of a 'continuous water-supply' scheme. Fileciteturn 8 file0L32-L34 file0L58-L64 file0L307-L325]availability

10. EXISTING NETWORK AND HYDRAULIC-ENERGY COUPLING

The hydraulic report provided quantifies the current distribution-network length as about 2659.8 km. Several pipe materials and diameters are present in the network and the city is supplied through feeders. Fileciteturn 9 file 8L505-L587 Similarly, for renewable energy studies, this hydraulic network could be coupled to pump schedules and storage tank levels. A coupled model could optimize the timing of high renewable energy generation for pumping that can happen without over-pressurizing or under-pressurizing the system. This way, energy-water optimization problem is defined rather than an electricity dispatch problem.

Indicator	Purpose
Renewable penetration	Measure share of instantaneous load supplied by PV and wind
Annual grid-energy reduction	Measure energy-offset benefit
PCC voltage deviation	Assess voltage quality
Minimum bus voltage	Identify weak pumping buses
Frequency deviation	Assess disturbance response
Damping ratio	Assess small-signal stability
Transient settling time	Measure recovery after disturbances
PCC THD	Assess harmonic performance
Power factor	Assess grid-side reactive operation
Transformer loading	Assess electrical infrastructure stress
Renewable curtailment	Measure unused renewable availability
Water-supply reliability	Ensure electrical optimization does not compromise service

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12. EXPECTED RESEARCH CONTRIBUTIONS

The paper gives a massive municipal-infrastructure case for testing hybrid-renewable integration with pumping-heavy loads. Instead of looking at renewable-generation potential based on annual energy production alone, it links the hydraulic behavior of raw-water and pure-water pumping to power system stability assessment.
The second contribution is the integration of SCADA and hydraulic modelling with the EMS. The approach presented is capable of scheduling renewable supported pumping based on measured pumping energy, water levels and network status. The third contribution is the systematic assessment of converter stability, motor starting and grid disturbances at a municipal water-supply scale.

13. LIMITATIONS AND REQUIRED ADDITIONAL DATA

Data required	Use in research
Approved electrical single-line diagram	Electrical network model
Pump motor ratings and efficiency	Motor/load model
Pump-starting method	Transient stability
Transformer ratings and impedance	Power flow/fault analysis
Feeder impedance and conductor data	Voltage stability
Grid short-circuit level	Converter-grid interaction
Solar irradiance/temperature time series	PV model
Wind-speed time series and turbine curve	WECS model
PV inverter control parameters	Small-signal analysis
WECS converter/control parameters	Dynamic analysis
Protection and ride-through settings	Fault simulation
SCADA electrical and hydraulic time series	Model validation

14. DISCUSSION

Environmentally-based renewable-energy stability studies may be particularly well-suited to the Indore project given the nature of the water conveyance proposals. These include very large pumping flows and heads in conjunction with substations, transmission connectivity, and SCADA. The Phase-I project summary lists a 132 kV line and 132 kV substation, implying that the proposed water-supply facilities have a very large electrical interface (fileciteturn 9 file 5L315-L360). The raw-water pumping main in the Phase-I scheme is sized for 412 MLD and the pure-water pumping system incorporates a 400 MLD WTP-to-Booster Station component and a 580 MLD Booster Station-to-BPT segment (fileciteturn9 file 6L381-L396). These sizes include such large pumping duties that behaviour of the motor-load appears critical to the stability analysis.
The 126-day intermittent water-supply condition enables the opportunity for the research. As a guiding principle, the objective would be to move towards a continuous water-supply operation, so SCADA data can be used to generate realistic electrical demand curves. The renewable dispatch can then be planned to adjust the hydraulic storage and pumping schedules, tested using both electrical stability and hydraulic service-level criteria. The specifications on the provided documents do not allow the assessment of the PV or WECS installed capacity, so the proposed diagram and equations are only intended as a research extension of the water-supply project, not as an initial renewable-energy solution to the DPR.

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15. CONCLUSION

This paper presents a comprehensive stabily analysis framework of a grid-connected hybrid renewable energy system, consisting of solar PV and WECS, for the project of Indore Water Supply. According to the source DPR there is a present supply of about 436 MLD, service of 147 LPCD,and a service rate of about 29.39 lakh population to be covered by Indore Water Supply and has a strategic aim of shifting from intermittent water to uninterrupted water quality. Filециteturn 8 file 9L749-L756 The project comprises a proposed 1650 MLD Narmada intake, 400 MLD WTP, 18 raw-water pumping stations, six pure-water pumping stations at the WTP, Booster Station pumping, substations, SCADA, and a 132 kV electrical supply scheme. Fileciteturn 9file 4L257-L296

The panel-funded research will appraise this infrastructure by steady-state, voltage, small-signal, transient and power-quality analyses. The main technical concern is the interaction between converter-based renewable energy and large motor-driven pumping loads. Consequently, active/reactive set-point control and SCADA-based EMS are implied. Before grid numerical PV-WECS dimensions or stability-margins appear, the subsequent phase should secure the authorized electrical-model structure, motor and transformer details, renewable-resources data, inverter control-set points and SCADA data records. With these inputs, the method can be quickened into a verified MATLAB/ Simulink, DIg SILENT Power Factory or PSCAD research-mode

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SOURCE INTEGRITY STATEMENT

All project-specific facts pertaining to Indore in this paper are referenced from the provided Indore Water Supply DPR and hydraulic-report documentation. The solar PV plant, WECS, renewable capacity, dynamic converter models, control strategy and simulation scenarios are suggested research additions. The paper does not claim these as existing or endorsed features of the provided DPR. In cases where the project comprises several design phases or historical values, this paper preserves source terminology and suggests use of the most up-to-date endorsed design/equipment schedule for numerical modelling.