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MODELLING SMART REMOTE TERMINAL UNITS TO ACHIEVE POWER SUPPLY REDUNDANCY WITH OPTIMIZED BIOGAS PRODUCTION FOR ELECTRICITY COGENERATION AT EXISTING WASTEWATER TREATMENT PLANTS

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Abstract- Recognising the deep potential in wastewater treatment plant (WWTP) automation strategies, this paper focuses on expanding the plant operations in order to optimally utilise biogas production during the water treatment process to achieve electricity cogeneration and achieve High Voltage/ Low Voltage (HV/LV) redundancy. The research has resulted in a proposed design of a smart Remote Terminal Unit (RTU). The philosophy provides proper telemetric signal monitoring, enables two-way power flow and reduces intertripping downtime between WWTP distribution and the power company`s zone substations enabling a failsafe mechanism at different levels of water treatment process and biogas production, thus facilitating an automated WWTP electricity cogeneration. The proposed design also increases the life span of substations, reduces power demand load on the grids and enhances safety of WWTPs equipment during various scenarios of electricity cogeneration, shut downs and maintenance operations.

Index Term- biogas, cogeneration, electricity, health and safety, power management, remote terminal unit, smart grid, Wastewater treatment plant.

1. INTRODUCTION

Water is the main resource that plays a significant and predominant role in the existence of life on earth. It is also an important source of electrical energy. With the ever-increasing population and immense pressure on existing water resources, there is a universal realisation towards innovating new sources of energy and its conservation. Electrical engineers are working towards achieving sustainable solutions for enhancing energy production and efficiency methods by integrating renewable energy to daily usage [1, 2]. WWTPs consume high energy! In the US only, energy consumption for the movement and water treatment has been estimated to be 3-4% of the total electricity consumption [3]. The existing and old WWTP infrastructure lacks certain important features like monitoring, controlling, equipment protection and power supply redundancy that could enhance energy efficiency and optimally utilise the bio-fuels formed in the treatment process.

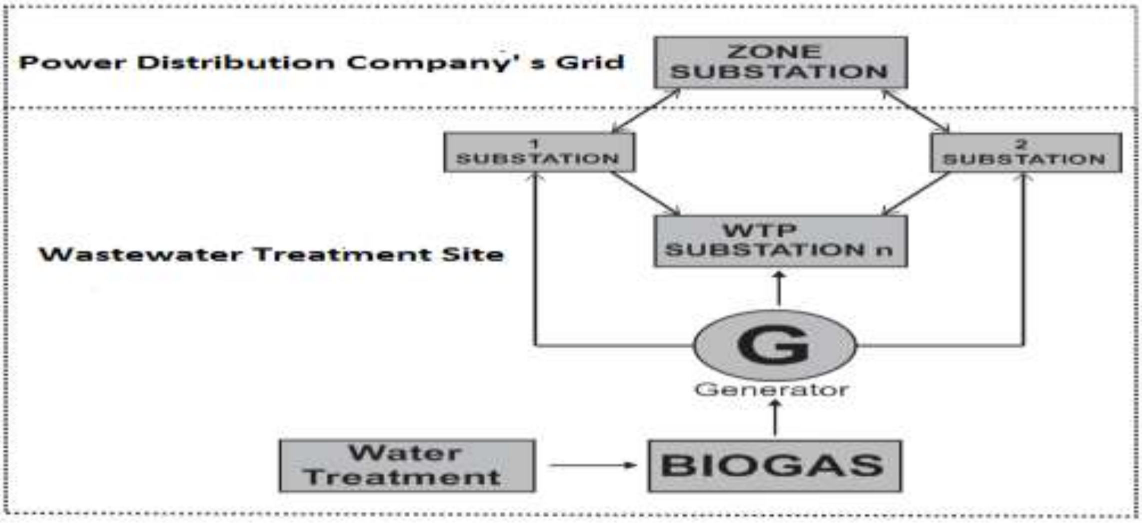

Fig. 1.1 Typical Arrangement for Electricity Cogeneration at WWTP

Implementing proper control and modelling philosophies with the help of smart RTUs at WWTPs and power company`s zone substations of the existing power distribution network, can address the issue of extensive energy utilization.

This paper aims to address these features by proposing a technology driven approach to optimise WWTP electricity cogeneration on existing infrastructure by enhancing protection, monitoring and control levels for smart metering and two-way power flow between the grids and WWTP or, any site where biogas or any other renewable energy resource is available. Typical arrangement for cogeneration at WWTP in ring topology is shown in the power flowchart of (Fig. 1.1) Biogas is produced and then utilised to excite on-site generators with controlled two-way power flow between distribution and zone substations.

1.1 Wastewater Treatment Methods

The four defined basic levels involved in wastewater treatment are shown in (Fig. 1.2)

1.1.1 Preliminary Level

Handles the physical separation of solids from the waste flow to avoid mechanical destruction of equipment downstream.

1.1.2 Primary Level

Involves the settlement of unwanted solids that are removed from the wastewater through screening and sedimentation, from which the effluent by product carries substantial organic material and is then biologically processed

1.1.3 Secondary Level

For further purification where residual suspended solids are eliminated using various microorganisms in a controlled environment. The treated secondary effluent is then channelled to huge ponds where it enters in the advanced level

1.1.4 Tertiary Level

Where sludge is produced. Waste Activated Sludge (WAS) process offers efficient removal of Chemical O_2 Demand (COD) for biogas production [4, 5].

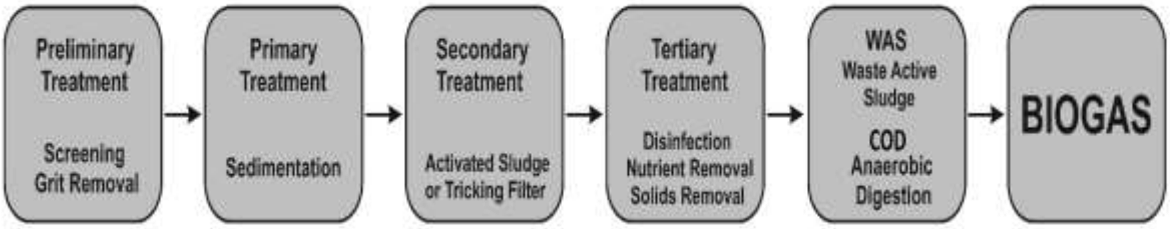

Fig. 1.2 Basic Levels of Wastewater Treatment

Mathematical model for biodegradable fraction of WAS [6] is represented in equation (1).

$$X = X_{active} + X_{active}(1 - f_d)K_d^{AS}SRT^{AS}$$
$$f_d^{WAS} = f_d \frac{X_{active}}{X} \qquad 1.1$$

Where
f_d^{WAS} = biodegradable function of WAS
X_{active} , X = total concentration of the volatile suspended solid(kg/m^3)
f_d = net biodegradable fraction of active biomass
K_d^{AS} = decay coefficient in the active sludge (day^{-1})
SRT^{AS} = solid retenion time applied in the active sludge process (day)

WAS has a high spoilable organic matter content, which is treated to ensure its stability and utilisation to full capacity before disposal. Two well-known digestion methods that serve this conversion are aerobic and anaerobic digestion.

1.2 Aerobic, Anaerobic Digestion Process and Biogas Production.

1.2.1 Aerobic Digestion

Aerobic digestion uses O2 to decompose organic contents produced in the presence of bacteria. The process is based on endogenous respiration where microorganisms start digesting their own protoplasm to gain energy and create “Flock”, which is in the form of stable sludge that settles down at the bottom of huge ponds and can be disposed of easily [4].

1.2.2 Anaerobic Digestion

Anaerobic digestion involves series of biological processes where degradation of organic content takes place in the absence of O_2 to produce biogas and bio-fertilisers. A Methanogen bacterium produces biogas (methane) through anaerobic reparation [5]. The generated biogas acts as a fuel for production of electrical energy through on-site generators. (Fig. 1.3) explains the type of gas produced during aerobic and anaerobic digestion. Biological process in WAS converts sludge into COD, which is a substrate utilised by the anaerobic digesters.

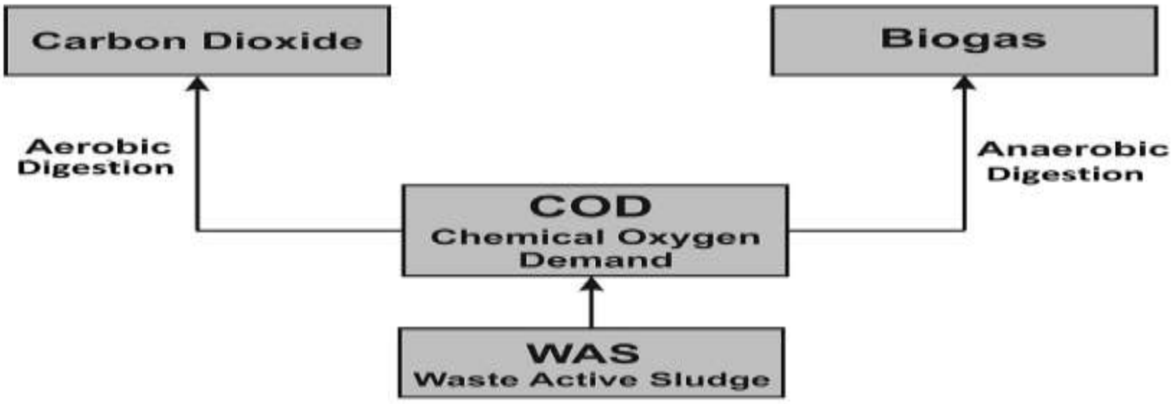

Fig. 1.3 Aerobic and Anaerobic Digestion

1.3 Mathematical Modelling for Biogas Production

The amount of biogas produced [6] can be calculated by equation (1.2).

$$s_o = COD_{in} f_d \left(\frac{X_{biod}}{X}\right)$$

$$\text{specific gas production (SGP)} = 0.23e^{-0.028SRT} \qquad 1.2$$

Where
s_o = substrate influent (kg/m^3)
COD_{in} = Chemical oxygen demand (kg/m^3)
X_{active} , X = total concentration of the volatile suspended solid(kg/m^3)
f_d = net biodegradable fraction of active biomass
SRT = Solid retenion time (day)
specific gas production = (m^3/day , V_s) , V_s volatile substrate influent feed

Through multiple microbial reactions, different products are being synthesised at prior stages of water treatment process. This acts as substrate for microorganisms in the next stage. One-stage nonlinear reaction modelling for anaerobic digestion [7] is shown in equation (3).

$$Q = K_2 \mu S \qquad 1.3$$

Where
Q = biomass flow rate (day^{-1})
K_2 = yield coefficient
μ = Specific growth rate(C^0/day)
S = Substrate (acetate)concentration (gl^{-1})

Biological kinetic equations (1.4) and (1.5) shows microbial growth and substrate consumption rate [8]

Grau et al kinetic model

$$S = \frac{S_o(1 + bt_{SRT})}{\mu_{max} t_{SRT}}$$

$$-\frac{dS}{dt} = \frac{\mu_{max} XS}{YS_o} \qquad 1.4$$

Monod kinetic Model

$$S = \frac{K_s\,(1 + bt_{SRT})}{t_{SRT}(\mu_{max} - b) - 1}$$

$$-\frac{dS}{dt} = \frac{\mu_{max} XS}{Y(K_s + S)} \qquad 1.5$$

Where
μ_{max} = maximum specific growth rate coefficent
X = micoorganism concentration (gl^{-1})
b = specific microorganism decay rate (day^{-1})
y = growth yeild coefficent
S_o , S = concentration of the growth limiting substrate in the influent and effluent (gl^{-1})
t_{SRT} = solid retention time (day^{-1})
K_s = half saturation coefficient
K_{max} = maximum specific substrate use rate (day^{-1})

Equation (1.2) indicates that biodegraded substrate in the anaerobic digestion process is time dependent. Equation (1.3) shows that the production of biogas varies with temperature. Equation (4) and (5) states that production of biogas depends on the amount of substrate produced. Hence, three main factors directly effecting the WWTP biogas production through anaerobic digestion process are time, temperature and the amount of substrate produced which needs to be taken into account while designing an efficient WWTP and their electricity cogeneration process.

1.4 CHP Process and Electricity Generation

Anaerobic digestion in bio-solid digesters section produces maximum amount of methane gas through combined heat and power (CHP) process. The sequential treatment flow process is shown in (Fig. 1.4) Flammable gases formed are burnt to produce sufficient amount of steam, which is further utilised to excite on-site generators for electricity generation [9].

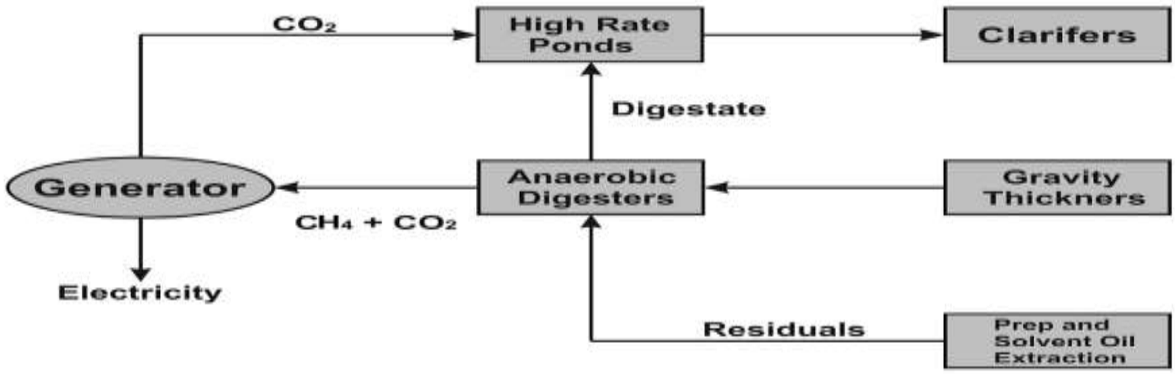

Fig. 1.4 CHP Process and Power Generation

Biogas is captured and utilised for on-site electricity generation through an internal combustion turbine while the heat generated during the process is used for increasing temperature of anaerobic digesters, especially in Winters, as higher temperatures favours this process. Electricity generation with waste heat usage is CHP process [9, 10], as shown in (Fig. 1.5). This is the most efficient way to generate electricity at WWTPs. Heat required for CHP process is shown [11] in equation (1.6) and clearly indicates its dependency on digester temperatures and WAS.

$$Q_{start} = cm\Delta Tt + Q_{lost} \qquad 1.6$$

Where
Q_{start} = Heat need to start anerobic process (kWh)
c = Heat capcity of feedstock (kWh/t/ h)
m = mass flow t/h
ΔT = change in feedstock temperature, before and after feeding into digester
Q_{lost} = heat losses through digester surface (kWh)

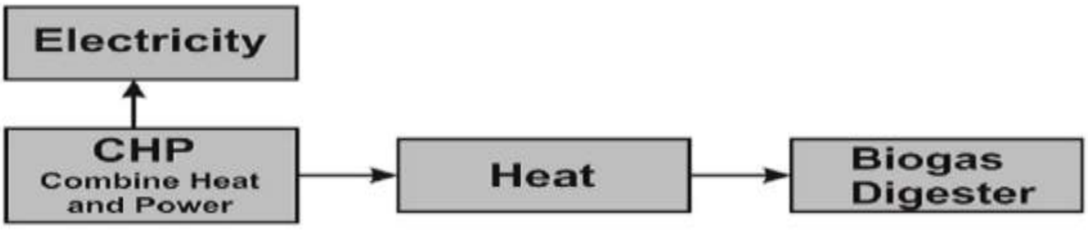

Fig. 1.5 Heat Flow in CHP Systems

CHP process provides sustainable means of power generation thus fulfilling the energy intensive requirements of water treatment process. Equation (1.7) presents power generation model using biogas [12] and indicates that power cogeneration system depends on the production of biogas and is directly proportional to each other.

$$m_{biogas} = f_d^{WAS} \times Y$$
$$MW = m_{biogas} \times y \times S \times \rho_{CH_4} \times LHV_{biogas} \times 1.165 \times 10^{-5} \times \eta_{el} \qquad 1.7$$

Where

m_{biogas} = mass florate of biogas (m^3/h)
f_d^{WAS} = biodegradable function of WAS
Y = biogas flow rate m^3/h
m_{biogas} = mass flow rate of biogas (m^3/h)
y = biogas yeild (m^3/kg)
S = methane fraction
ρ_{CH_4} = density of methane ($tons/m^3$)
LHV_{biogas} = lower heating value of biogas (MJ/kg)
η_{el} = Efficiency in percentage

The calculation of total system efficiency that evaluates power cogeneration with consumed energy [13] is given by equation (1.8).

$$\eta_o = \frac{W_E + \Sigma Q_{therm}}{Q_{fuel}} \qquad 1.8$$

Where

η_o = total system efficency
W_E = electrical output (Watts)
Q_{them} = thermal energy output joules per second (heat transfer rate Watts)
Q_{fuel} = fuel consumption Joules per second (energy tranfer rate Watts)

(Fig. 1.6) evaluations taken through statistical calculations of conventional and CHP power systems at various WWTPs [14].

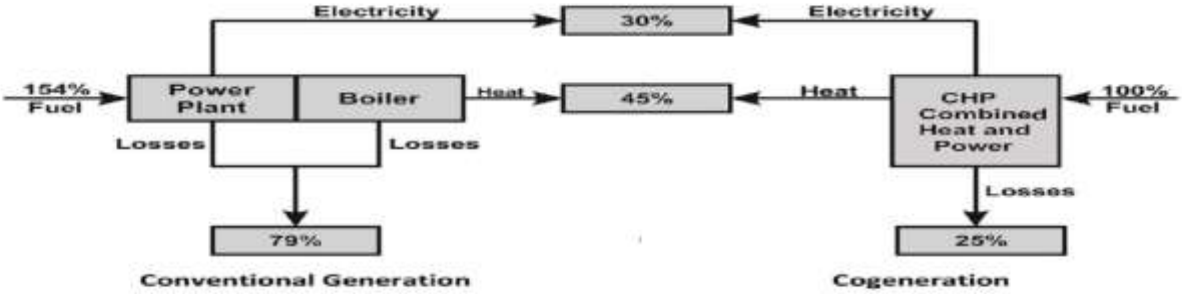

Fig. 1.6 CHP System Efficiency [14]

2. Problem Statement

2.1 Variations in Biogas and Scenarios for Electricity Cogeneration

Dependency of WWTP electricity generation on biogas production develops three different scenarios of electricity cogeneration.

- **WWTP power generation < demand load**
- **WWTP power generation = demand load and**
- **WWTP power generation > demand load**

WWTP therefore requires a robust automated system to manage these scenarios that also provides a systematic and layered protective system to substation equipment. (Fig. 2.1) simulation results at MW-WTP shows that production of biogas is not consistent with time and temperature.

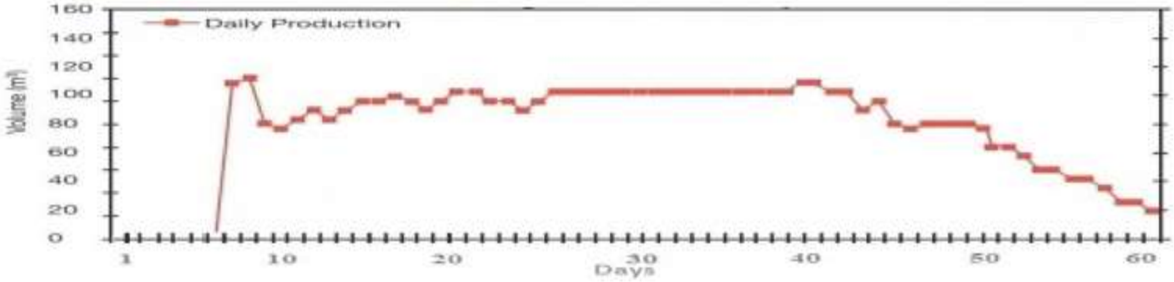

Fig. 2.1 Daily Production of Biogas

(Fig. 2.2) simulation data has been obtained at different temperatures for anaerobic digestion process at MW - WTP. Results show that high temperatures favour anaerobic digestion and relative biogas yield increases with the increase in temperature and stabilises after reaching its peak value [15].

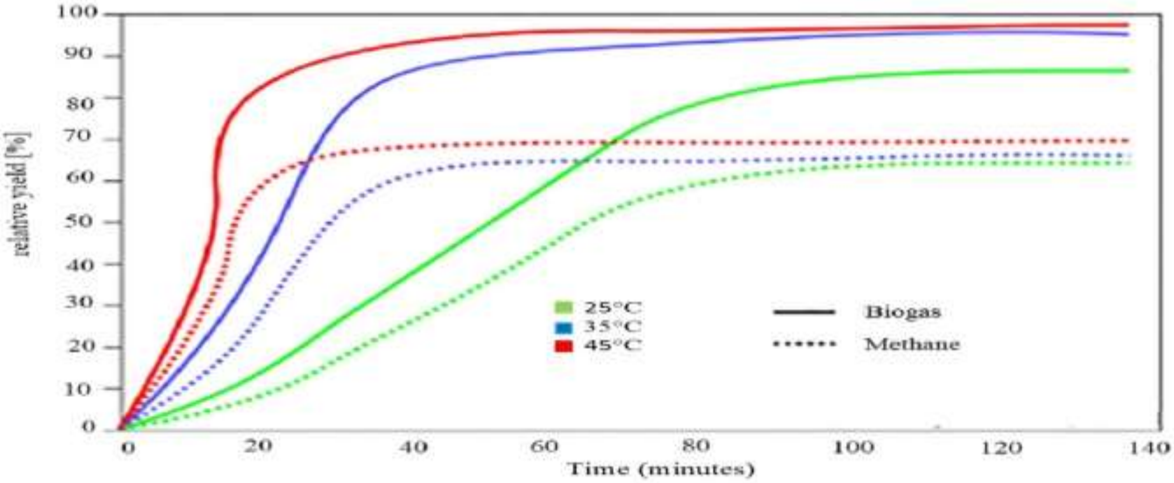

Fig. 2.2 Relative Biogas and Methane Yields for Different Temperatures at MW-WTP

2.2 Existing and Old WWTP Infrastructure

Varying amount of biogas production reduces efficiency of existing WWTP infrastructure due to an inefficient communication network system and lack of a protection coordination, centralised metering and monitoring system during electricity generation process, which provides interlocking and intertripping mechanism with the power company`s zone substation. Complex secondary designs like telemetric signals, protective relaying and control gear monitoring needs to be reduced for implementing a flexible infrastructure with adequate redundancy [16].

2.3 Power Management Issues

Water treatment is an energy intensive process that puts huge loads on the power company`s grid, making it very expensive. Existing WWTPs require alteration and upgrades to reduce this excessive load. (Fig. 2.3) shows power demand load at different levels of water treatment process at Melbourne Water Western Treatment Plant (MW-WTP) in Australia, which is the largest treatment facility in the southern hemisphere. It is clearly noted that the demand is very high, especially during the preliminary phase. It requires an automated, failsafe and redundant way for WWTP electricity cogeneration. Existing MW-WTP substations has no proper system to supply surplus generated electricity to the power company`s grid [17].

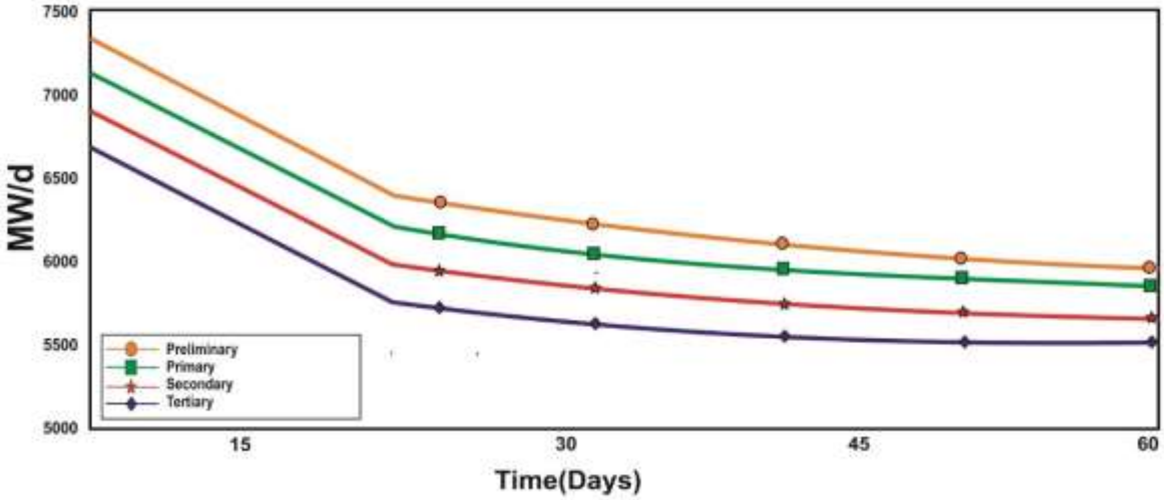

Fig. 2.3 Demand Load for Water Treatment Process Levels at MW-WTP

(Fig. 2.4) shows average demand load verses power generation at MW-WTP existing infrastructure. Simulation results show that power demand is mostly higher than its generation because of an inefficient power management system (PMS) at MW-WTP. This generated electricity needs to be managed properly. It requires a failsafe monitoring and controlling system to effectively utilise WWTP biogas production to its maximum efficiency. WWTPs should be able to generate enough electricity through heat and waste energy to meet its own demand and, under ideal conditions, also be able to do reverse power generation.

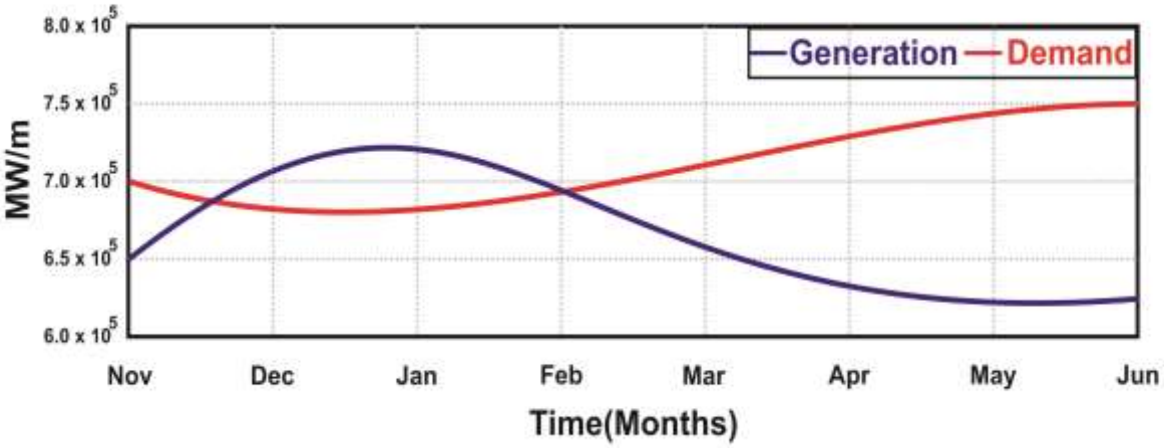

Fig. 2.4 Existing MW-WTP Demand Load Vs Power Generated

2.4 Intertripping Downtime

Efficient interlocking and intertripping philosophy between the WWTP and power company`s zone substations is required to handle different volumes of biogas produced for electricity cogeneration and abrupt variations. Intertripping downtime must be reduced for a swift and reliable operational control on WWTP equipment to achieve electricity cogeneration. Traditional secondary wiring of protection relays takes more than the required time to perform intertripping under faults and are extremely unreliable [18]. A philosophy must be developed to implement HV/LV interlocking of supplies to achieve redundancy, which existing WWTP infrastructure doesn`t offer.

2.5 Occupational Health and Safety (OH&S) Issues

Manual operator tasks in the existing WWTPs during HV switching for maintenance shutdowns and power outages, serve to increase risks. Physical interaction with HV equipment needs to be minimised during the complex task of electricity cogeneration [19].

2.6 Environmental Issues

Greenhouse gases (GHG) produced during the water treatment and electricity cogeneration process must be prevented to enter into the atmosphere to reduce environmental footprints of WWTPs. Existing infrastructure creates a bad impact on the odour and quality of the atmosphere. A redundant process is therefore required that can constantly monitor, control and utilise the biogas and the heat produced [20].

(Fig. 2.5) results show that the existing MW-WTP emits 80,000 tonnes GHG per year (approx.) into the atmosphere, which can be reduced by more than 30,000 tonnes by implementing proper electricity cogeneration and management model.

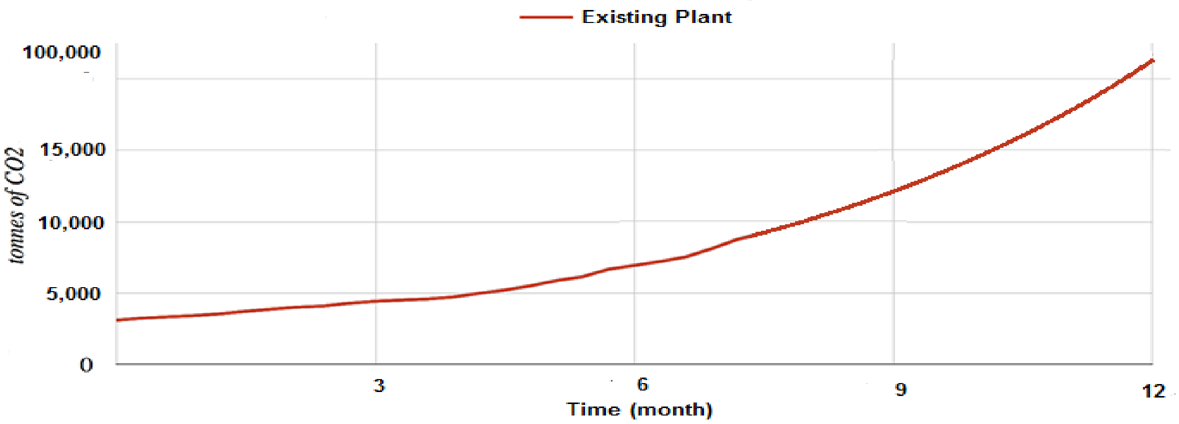

Fig. 2.5 GHG for the Existing MW-WTP

2.7 Asset Management Issues

Making existing WWTPs energy efficient and sustainable has been an expensive and challenging task for the stakeholders and asset managers. Replacing substations, synchronising new systems with existing or old systems, WWTP maintenance, shutdowns and power outages puts enormous burden on the budgets and profitability. Hence, an affordable system is required, which is easy to implement and maintain, to achieve electricity cogeneration and energy sustainability at existing WWTPs.

3. DEVELOPMENT OF PHILOSOPHIES AND METHODOLOGY - PROBLEM EVALUATION

3.1 IEC and IEEE Standards Implementation

IEC 61850 standard explains the model for accounting configuration of substation networks covering protection and control devices along with their connections. It also defines monitoring topologies utilizing substation configuration language (SCL) for SAS. IEC 61850-8-1 protocol uses object oriented configurations for reliable remote operation. IEC 61850-9 standard is compatible for conventional and modern CT/VT with converging devices [21]. IEC61850 with IEEE C37.238 performs reliable intertripping and interlocking of power supplies. Second and third Layer of open system interconnection (OSI) provides protection and reliable control. The Smart RTU philosophy should incorporate all these standards for a safe and successful WWTP electricity cogeneration. (Fig. 3.1) shows four OSI layers of protection used in the proposed philosophy for this research paper. Smart RTUs are implemented in the second layer.

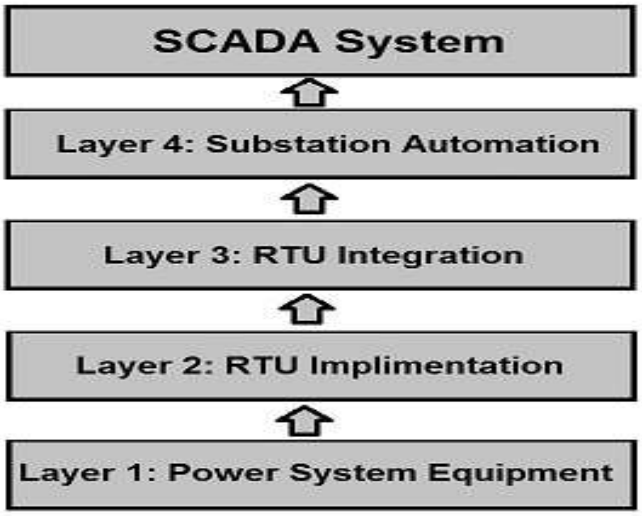

Fig. 3.1 Four Layers of OSI Protection via Smart RTUs

3.2 Power Management System (PMS)

Efficient WWTP power distribution network through self-power generation using biogas or any renewable resource, must have a failsafe mechanism of a two-way power flow. Adding redundant communication capacity to WWTP distribution substations does this whilst providing a centralised PMS. This will address aspects of substation automation systems (SAS), such as enhanced and reliable protection, supervisory control and reliability of power. Ethernet based communication system can facilitate complex intelligent automation of WWTP and power company`s zone substation. It also enables secure transmission of telemetric signals (tripping signals, synchronisation messages, CB status) for reliable operations and maintenance (O&M). This calls for development of customised smart RTUs that will efficiently control and manage power flows between the power company`s zone substation and the WWTP biogas fed installed generators by providing the required layers of protection.

3.3 SCADA System

To avail opportunities presented by the WWTP infrastructure, various tools and human machine interfaces (HMI) like SCADA system are used for monitoring and controlling. Smart RTUs are utilised as part of SCADA system with a goal to reinforce correspondence between the WWTP distribution substations, generators and power company`s zone substations. SCADA needs to assemble telemetric data of various power generation systems in order to ensure the availability of the entire substation’s information at a centralised location for common use [22]. Advance monitoring system (AMS) with SCADA system enhances quality of service, reliability, and security. AMS is deployed for continuous monitoring and metering solutions. It also provides a redundant two-way communication and is able to gather information on voltage, current and power [23].

3.4 Power Network of Zone and Distribution Substations to Achieve Hv/Lv Redundancy

(Fig. 3.2) represents two-way power flow in ring topology and typical equipment terminations of power company`s zone substation terminal with the two onsite WWTP distribution substations, termed as point of contact (shown as POC1, POC2 and POCn), for electricity cogeneration. Any number of substations can be connected to this network via Ring Main Units (RMU) for HV switching. The smart RTUs are connected with each POC and then interlinked with each other via a communication protocol.

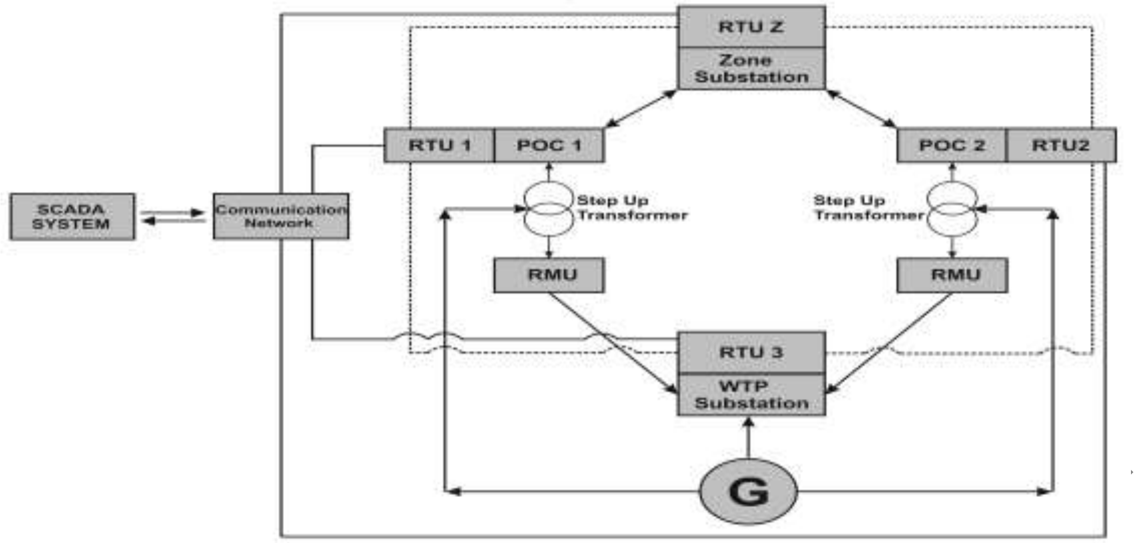

Fig. 3.2 Ring Topology of Substation Network at WWTP

3.5 Intertripping Philosophy

3.5.1 Protection Trips

Swift and efficient provision of protection trip signals to the relays and shunt trip coils of relevant circuit breaker (CB) protects each substation. These signals are generated from auxiliaries and contactors of various power equipment at WWTP and the power company`s zone substation. Controlled intertripping mechanism is necessary to direct tripping commands, in the form of telemetric signals, in order to protect the power systems during various scenarios of electricity cogeneration. Mapping and communication of these telemetric signals can be achieved by installing smart RTUs at each POC of the WWTP and the power company`s zone substation.

3.5.2 Zone Substation Trip

Tripping signals are used when WWTP power generation is equal to its demand load so that the feeders are disconnected from their respective POCs. Operating WWTPs at any given instance of electricity cogeneration scenario requires a robust and a swift way to communicate this tripping command, to and from power company`s zone substation.

3.5.3 Fault Trip

Fault current must be stifled rapidly so that the equipment’s tolerance does not exceed its threshold and the restart/reconnect action of WWTP generators with the power network can be triggered at the earliest opportunity. Faults due to short-circuiting can be managed by tripping the power supply from the associated substation unit so that it is isolated from the faulty part of the circuit. With the aim of rapid fault detection and system restart, it is necessary to plan detailed protection relay coordination beforehand. This mapping philosophy then needs to be communicated across the power network for appropriate safety actions, in a sequential way.

3.5.4 Remote Trip

This signal acts like a field isolator and is able to trip any specific substation, when required manually. When power company`s zone substation wants to perform maintenance related task, the design philosophy of the WWTP electrical cogeneration modelling must ensure triggering of a remote trip signal. In response, power generated at WWTPs must be tripped to prevent reverse power generation process, as the grid is not ready. For a smooth and safe operation, the design philosophy at power company`s zone substation ensures that a remote trip signal conveyed from WWTP distribution substations will not cause the relevant POC to trip unless at least one of the WWTP generators is operating parallel to that particular feeder coming from the power company`s zone substation [18].

3.5.6 Intertripping Downtime

Intertripping of HV and LV CBs of WWTP power network must be automatically activated and operated with a reduced downtime. Reducing intertripping downtime between power equipment increases their safety and protection during the electricity cogeneration process. Smart RTU philosophy must incorporate a communication network that is able to transmit the tripping signals in the form of telemetric I/Os (Input/Output), rapidly and efficiently. HV intertripping is achieved by activating the shunt trip coil in the switchgear via the smart RTUs telemetric fault signals, installed at each substation.

3.6 Interlocking of HV/LV Power Supplies

Interlocking of HV/LV power supplies at WWTPs ensure that the network components (CBs, isolators, generators, feeders) operate without any manual tasks and commands during the electricity cogeneration process. Automation of this sensitive system requires status information of CBs (open, close or trip) at POCs, in order to provide redundancy through smart RTUs. Disconnection of WWTP generators should ensure that a trip and successful auto-reclose of power company`s zone substation feeders restore supply to their respective POC. Hence, it must also inhibit the operator initiated remote trip for the incoming feeders when generators are not connected to them. WWTP generators are interlocked with the zone and distribution substations via smart RTUs. RMU provides HV switching point and enables improvement in secondary distribution network performance by providing HV redundancy to the POCs via an alternate feeder when required. [24, 25].

LV supplies from the WWTP generators are interlocked with LV supplies of the POCs using auto-transfer-switching (ATS) panels, CBs of which are mechanically and electrically interlocked to the CBs of main LV switchboard of each POC. ATS serves to protect the distribution substations during WWTP electricity cogeneration, by triggering signals to make or break a contact via smart RTUs, when required. HV/LV power supply interlocking philosophy and scenarios are highly dependent biogas production on-site.

3.6.1 HV and LV Reticulation and Redundancy

Schematics for the MW-WTP HV/LV reticulation and the interlocking are shown in (Fig. 3.3). The nine MW-WTP 1.5 MW generators supplies LV to POCs. Surplus power is being fed back to the power company`s zone substation though high frequency transformers and reverse power relay (RPR). The mechanical and electrical interlocking of LV supplies between the plant generators and POCs provide a protection layer and LV redundancy during the electricity cogeneration process. HV redundancy is achieved by connecting feeders at POC1 and POC2 with all the other WWTP substations in ring topology via RMUs, which also provide HV switching points.

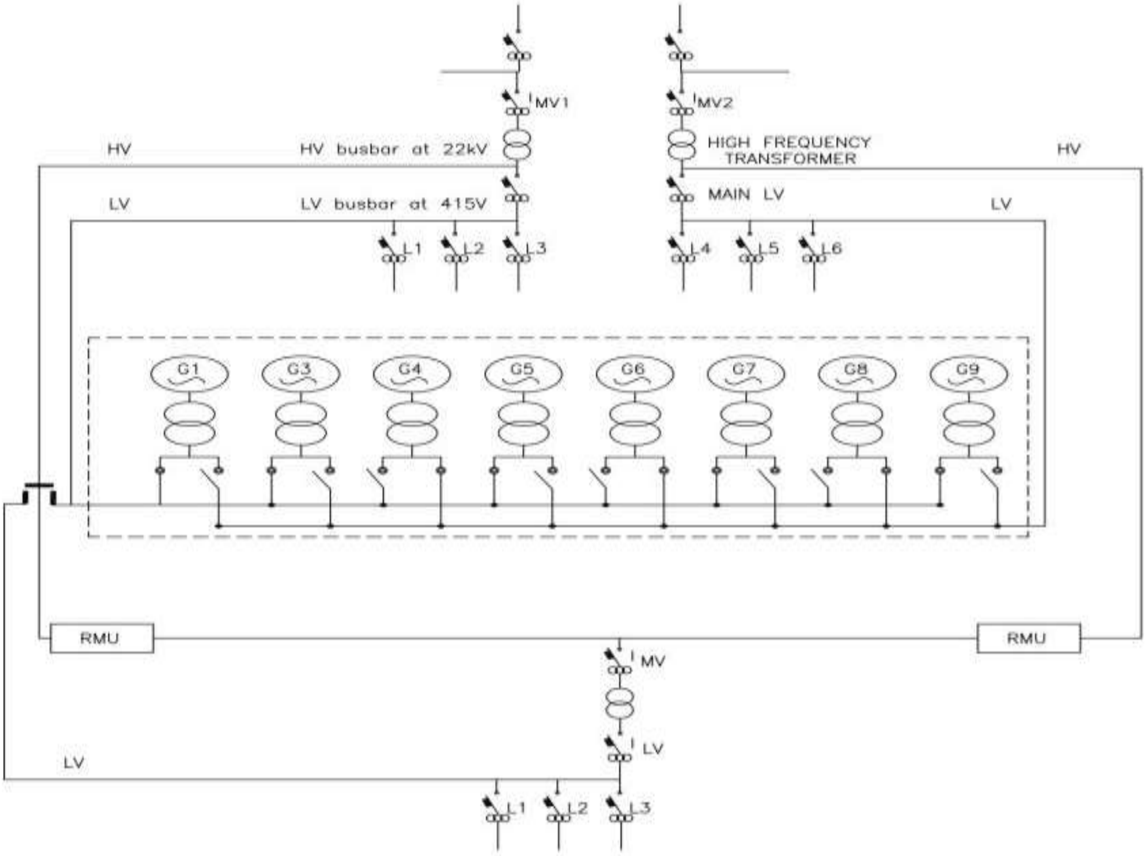

Fig. 3.3 Ring Topology for HV/LV Reticulation and Interlocking at MW-WTP

3.7 Enable POC Reverse Power Relay (RPR)

RPRs are utilised to detect power spill outs of generators. POCs RPR becomes functional when WWTP generates surplus or less electricity than its demand. A timer is initiated by this I/O, which at the end of a defined period enables the associated POC's RPR. This relay comprises of three parts namely directional, delay and hold. Current transformer (CT) and voltage transformer (VT) signals are changed over to a pure square wave shape having two levels, +1 and -1 respectively. For overlapping and non-overlapping sessions, +1 and -1 are obtained. The result is also subject to integration. In case of electricity cogeneration, this I/O attains threshold value. The delay component provides protection for relays by averting false trip signals delivered to the CB of the respective POC. The hold block provides stability to relay state and the power network system, on getting tripped. Smart RTUs enable these functions when required, providing a layer of protection.

3.8 High Frequency Step-Up Transformers

When WWTP is generating surplus electricity, higher power frequency is maintained to reduce line losses during the WWTP reverse power generation to grid. High frequency step up transformer uses Ferrite toroidal cores to increase frequency of the reverse power. These frequencies range between 1KHz to 100MHz.The three-phase 415V supply system from WWTP generators are connected with these transformers, which steps-up potential to 1kV and increases the frequency of power during reverse power generation. These transformers distribute power efficiently where cogeneration is being implemented. Mathematical model for proposed philosophy in which the frequency of transformers can be calculated for effective reverse power generation is shown in equation (1.9).

$$f_t = \frac{V_h}{2.d.\pi^2.L_h.p_o}(\pi - \emptyset) \qquad 1.9$$

Where
f_t = frequency for transformer (Hz)
V_h = high voltage input (V)
d = voltage regulation (V)
L_h = leakage inductance ??
p_o = out power (Watt)
$\emptyset$ = phase shift angle (radian)

(Fig. 3.4) shows power distribution with high frequency for reliability to overcome inrush current in busbars of the POC switchgears due to two-way power flow, reducing overheating of busbars.

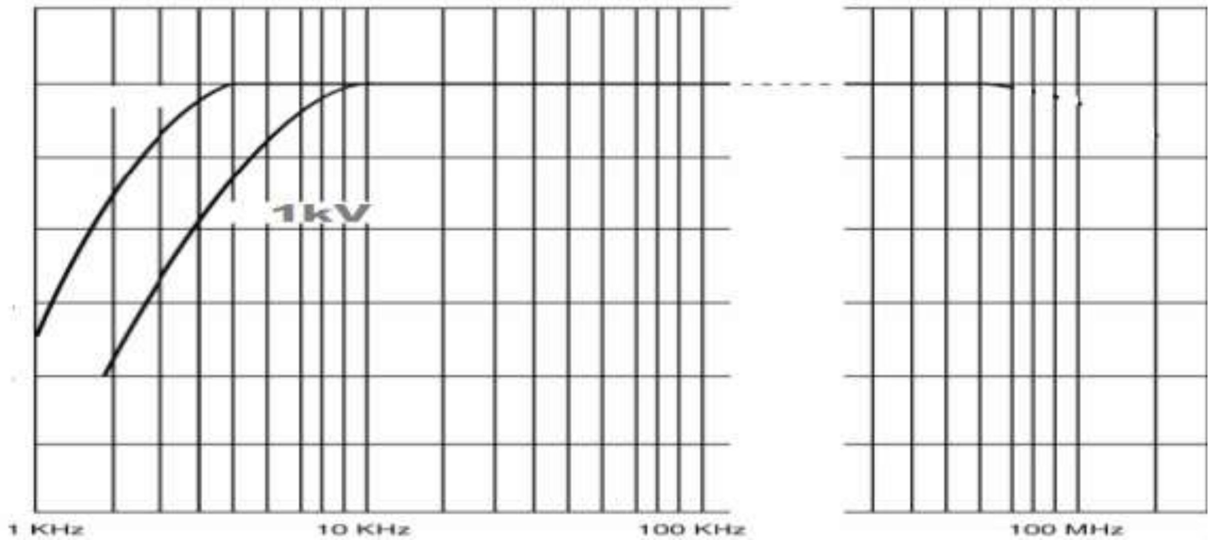

Fig. 3.4 High Frequency Curves for Reverse Power Generation

4. PROPOSED SMART RTU INTERFACE AND WWTP ELECTRICITY COGENERATION

The proposed smart RTU philosophy aims to set up suitable configurations and connectivity based on cost effectiveness, adequate ingress protection, reliable implementation, performance, and maintenance. The proposed design utilises remote and on-site controls for monitoring and managing protection trips, plant condition, supervision and faults indications. This network extension will seamlessly integrate with any existing or old WWTP infrastructure. Intertripping and interlocking philosophies are then developed with required telemetric signals made available to smart RTUs at a potential-free contact to optically isolate different control voltage levels from their respective substations [25, 26]. (Fig. 4.1) represents the proposed smart RTU interface. Telemetric signals are generated from the power company`s zone substation and WWTP. The wiring of each POC is based on design, telemetric I/O mapping and flow, interlocking and intertripping philosophy. These telemetric signals are calibrated via PLC and then onto an HMI via smart RTUS, for proper monitoring and control of WWTPs. The smart RTU contacts are energised by an external redundant source and communication redundancy is achieved by implementing FOC patch panels with a backup ADSL link. Tables 1 and 2 show smart RTUs interface for the type of telemetric I/Os, mapping and flow to perform WWTP electricity cogeneration process.

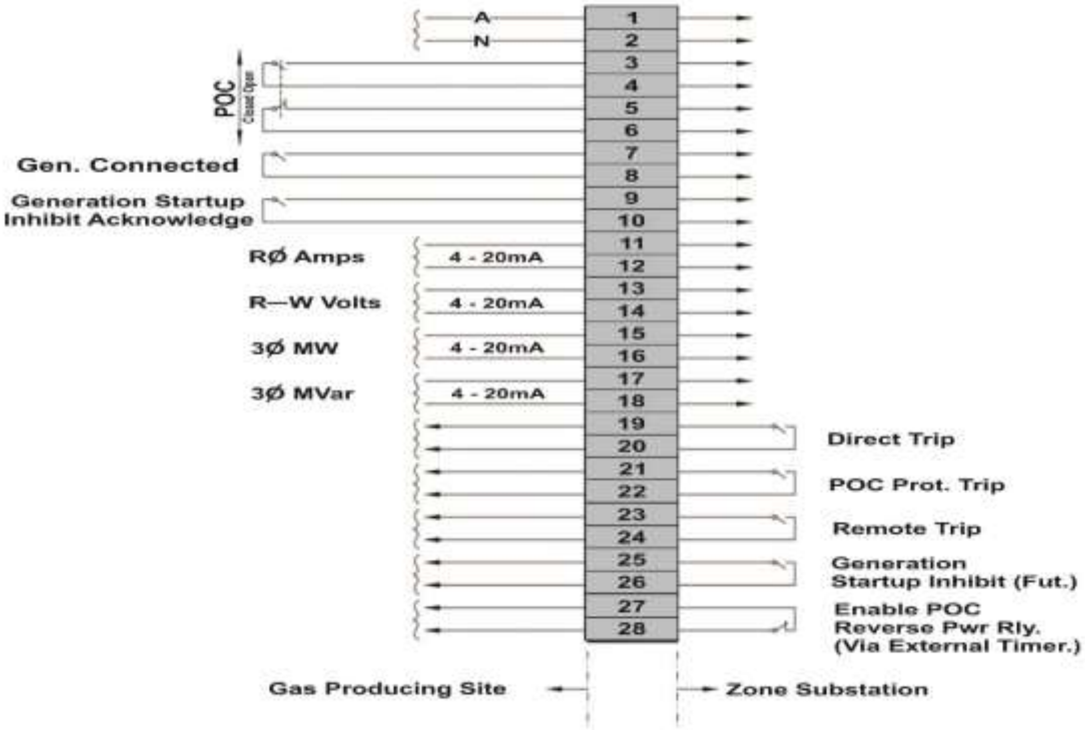

Fig. 4.1 Proposed Smart RTU Interface With Telemetric Signals

Table-4.1 Telemetric Signals at WWTP

Input point	Function	Device	I/O type
1-2	Power supply	UPS	24VDC supply
3-4	POC open	Auxiliary NC	Digital Input
5-6	POC close	Auxiliary NO	
7-8	Gen connection	Generator	Digital Output
9-10	Gen Acknowledgment	Relay	
11-12	R ϕ Amps	CT	Analog Input
13-14	R- Volts		
15-16	3ϕMW		
17-18	3ϕMVARs		

Table-4.2 Telemetric Signals at Power Company`s Zone Substation

Input point	Function	Device	I/O Type
19-20	Direct trip	Zone Substation Control Room	Digital Output
21-22	POC Prot. Trip	Protection Relays	
23-24	Remote trip	Control Relays	
25-26	Gen start-up Inhibit (fut.)	WWTP Generator Relays	
27-28	Enable POC reverse power	Relay External Timer	

5. SCENARIOS

5.1 Scenario One WWTP Power Generation < Maximum Demand Load

(Fig. 5.1) shows power flowchart for scenario when the amount of power generated from WWTP production of biogas < the demand load. In this case, the LV power supply from WWTP generators is interlocked to the priorities already allocated to the POCs. The CB of the top priority POC and the feeder is tripped. In this research, POC2 is given the first priority, assuming lesser demand load on its feeder. This calls for a situation where power must be supplied by both, WWTP generators as well as power company`s zone substation. The WWTP generator then supplies power to first prioritised POC (POC2 in Fig. 17) and any remaining power supply is directed to the next priority POC. The power company`s zone substation supplies remaining power as per WWTP demand load requirements via POC1 feeder. There could be a number of distribution substations (indicated as POCn) at WWTP. In this scenario, the LV switchyards of any POCs receive power supply from the WWTP generators based on pre-set priorities and interlocking philosophies. POCs with lower priority are fed from the power company`s zone substation. The protection relay trips HV feeders of the first priority POC, POC2 in this case, so that WWTP generator supplies power to its LV panels. If for any reason the generators are still connected to tripped feeders at the time of reclose, CBs of the first priority POC and its feeder will remain open as it is interlocked with the Generator Connected' status for the respective POC. The scenario usually occurs on cooler days and night when the temperature is low and the digestion process is slow.

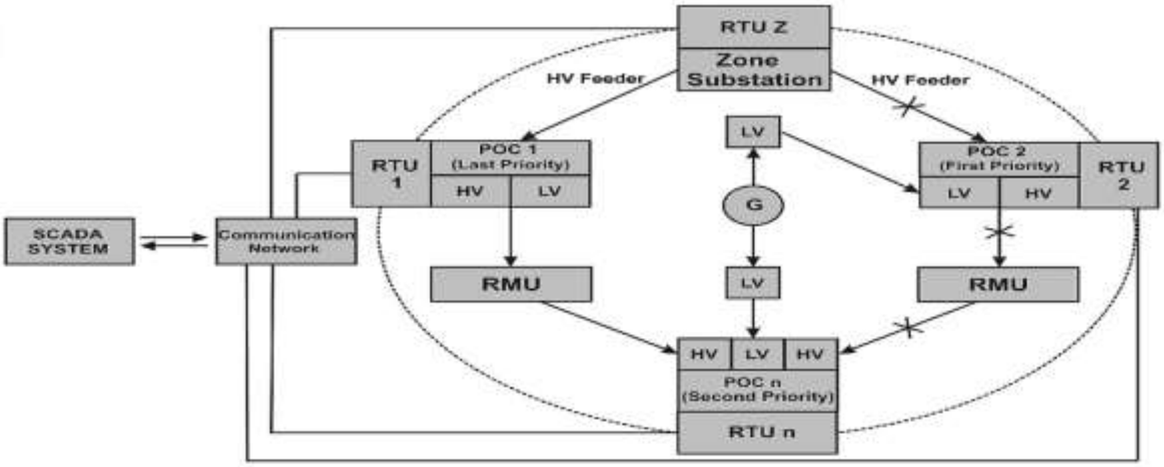

Fig. 5.1 Scenario one WWTP power generation < the maximum demand load

5.2 Scenario Two WWTP Power Generation = Maximum Demand Load

In this scenario, the power company`s supply is not required. (Fig. 5.2) for this scenario shows that the WWTP generators interlock with LVs of the POCs (POC2 then POCn then POC1), providing the first layer of system protection, where it sends a signal to power company`s zone substation tripping CBs of all the HV feeders connected to POC2 and POC1 respectively, ensuring a second layer of protection. Tripping signals generated from the auxiliaries of WWTP generators and POC switchgear are communicated via the smart RTUs installed at each POC and the power company`s zone substation.

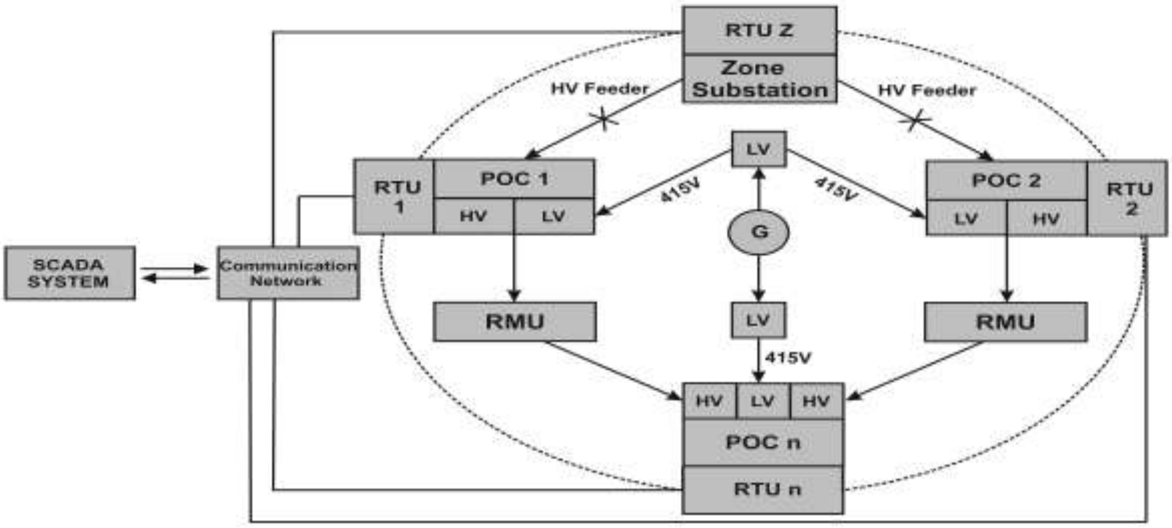

Fig. 5.2 Scenario Two WWTP Power Generation = Max Demand Load

5.3 Scenario Three WWTP Power Generation > Maximum Demand Load

Fig. 5.3 represents third scenario, which requires reverse power generation via WWTP POCs. The relevant feeders at power company`s zone substation will open. WWTP generator interlocks with ATS of POCs while the HV feeders are already tripped. Surplus power is fed back to the power company`s grid by enabling the RPRs. A generator inhibit request signal is sent as an acknowledgement to the POCs and power company`s zone substation, which then reinstates the POC1 and POC2 breakers. Surplus LV supply from WWTP generators is directed to high frequency a step-up transformer that further feeds the HVs of POC1 and POC2 enabling reverse power. The generator inhibit signal via the smart RTU panels, reinstates the tripped breakers of HV feeders at POCs after the LV interlocks have been established. This allows reverse power generation at higher voltage and frequency levels to minimise line losses and over-heating of POCs HV busbars.

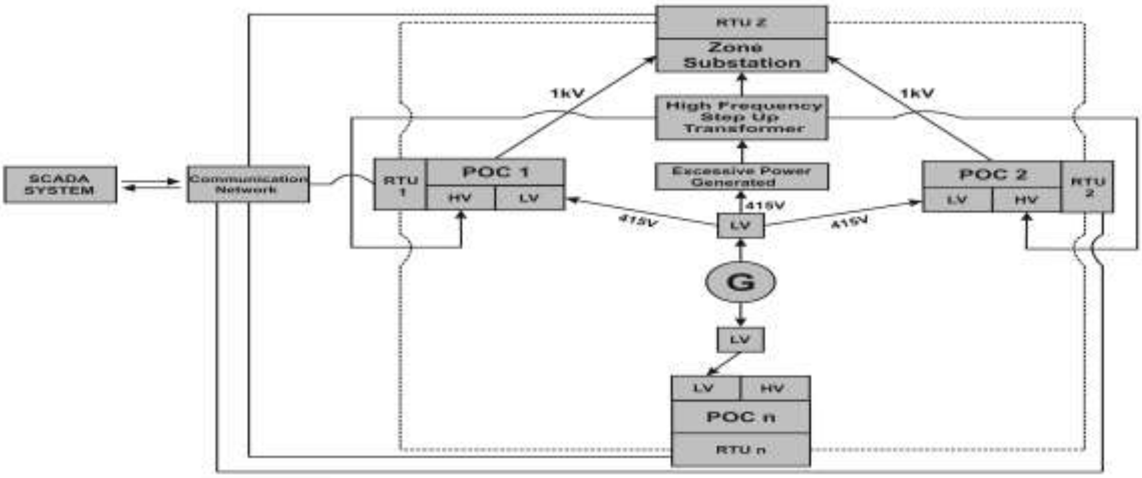

Fig. 5.3 Scenario Three WWTP Power Generation > Maximum Demand Load

6. RESULTS AND DISCUSSION

6.1 Power Network at MW -WTP

Stakeholders of existing and old WWTPs face strong challenges on issues related to power consumption, GHG emissions, operations and maintenance. Necessary follow-ups are therefore mandatory to verify the expected performance of the systems through modifications done in the existing infrastructure. A similar situation developed at the MW-WTP. The asset managers wanted to implement an effective, automated and failsafe way of enabling electricity cogeneration through on-site generators. Ring topology for the HV/LV power supplies was initially proposed as shown in Figure 12. The modelled smart RTU philosophy was then implemented at MW-WTP POCs and power company`s zone substation. Simulated results, after this economical upgrade to the existing infrastructure, are shown below.

6.2 Smart Metering Results

An estimate of MW-WTP power generated with respect to its average actual maximum demand load is studied to map out proper protection relay coordination at the POCs. If metering signals are not available, then CTs of appropriate ratios are mounted on the phases and then calibrated on the analogue module of the PLC. These telemetric analogue signals are then communicated to an HMI. Figure 20 simulation results show MW-WTP demand load for various wastewater treatment levels VS power generation. As compared to the results in (Fig. 6.1) data is more accurate, precise, discreet, efficiently obtained and communicated via the smart RTUs. These metering signals provide a proper monitoring platform to effectively develop an interlocking and intertripping philosophy of MW-WTP HV/LV supplies.

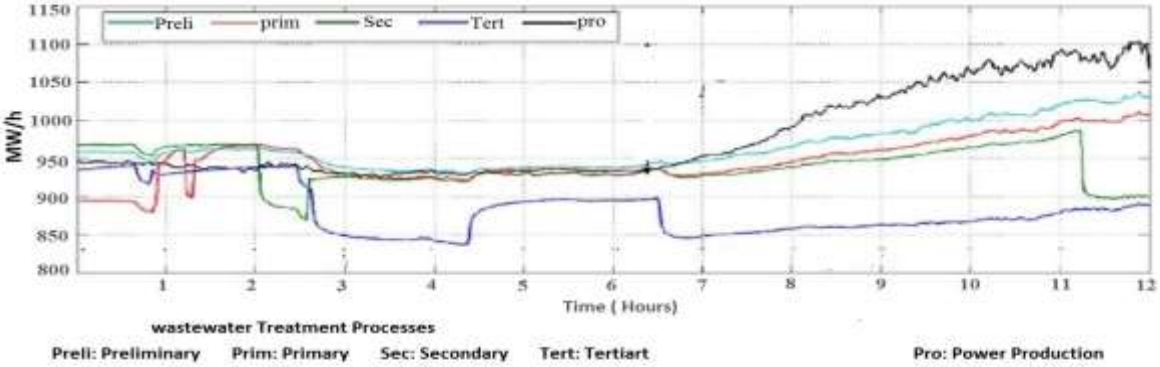

Fig. 6.1 Telemetric Power Monitoring at MW-WTP

6. 3 Availabilities of WWTP Telemetric Status Signals

The proposed design is served by telemetric signals redundancy that effectively conveys the status of energy demand and supply before any operation. Where system lacks availability of status signals, they can be made available through DC auxiliaries and interposing relays in the POC switchgear or simple upgradations. The smart RTUs provide a platform for all these I/Os to be accumulated for SCADA.

Simulation for over-current relay trip signals being generated under various scenarios of electricity cogeneration at MW-WTP is shown in (Fig. 6.2). The spike reflects correspondence relay action against over-current activities in the smart RTU. Results show an effective management of faults. When current exceeds its set threshold value, the protection relays trips instantly, isolating the power network from the defected part effectively and instantaneously.

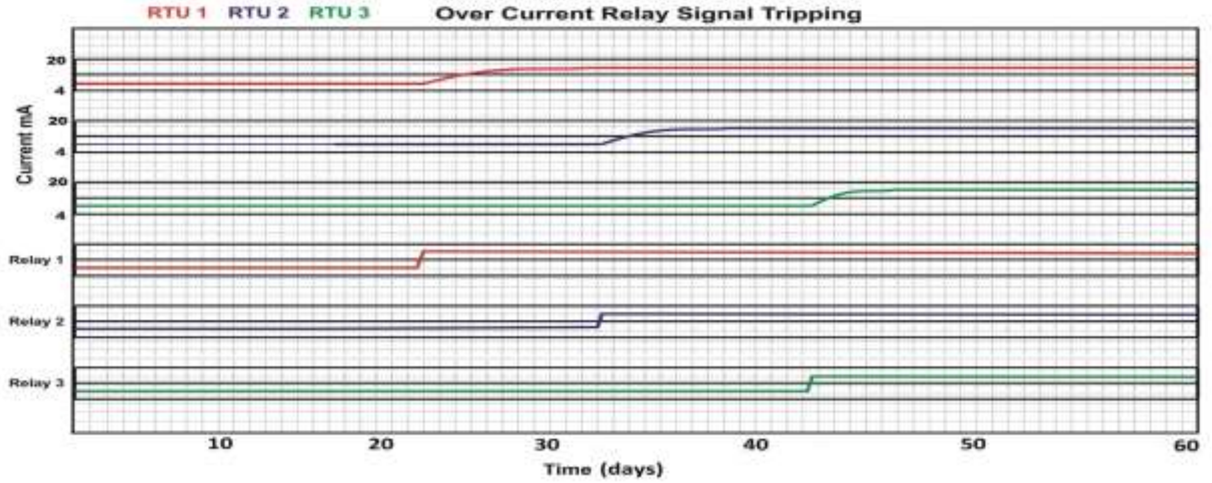

Fig. 6.2 Smart RTU Relay Action Against Over-Current

6.4 RPR

(Fig. 6.3) simulation results taken at MW-WTP show directional power relays action with smart RTUs under various scenarios of electricity cogeneration during the spring season. When power generated at the MW- WTP equals the demand, power relay1 trips to disconnect POCs from zone substation. At noon when biogas production increases due to increase in temperature, the RPR2 will trip for reverse power generation. During evenings, when power generated < the demand load, RPR3 trips to direct electrical power from zone substation to overcome the deficiency. These active relays can trip automatically and simultaneously with each step via the smart RTUs. POC intertripping and HV/LV interlocking provides effective controls and safety during the cogeneration process.

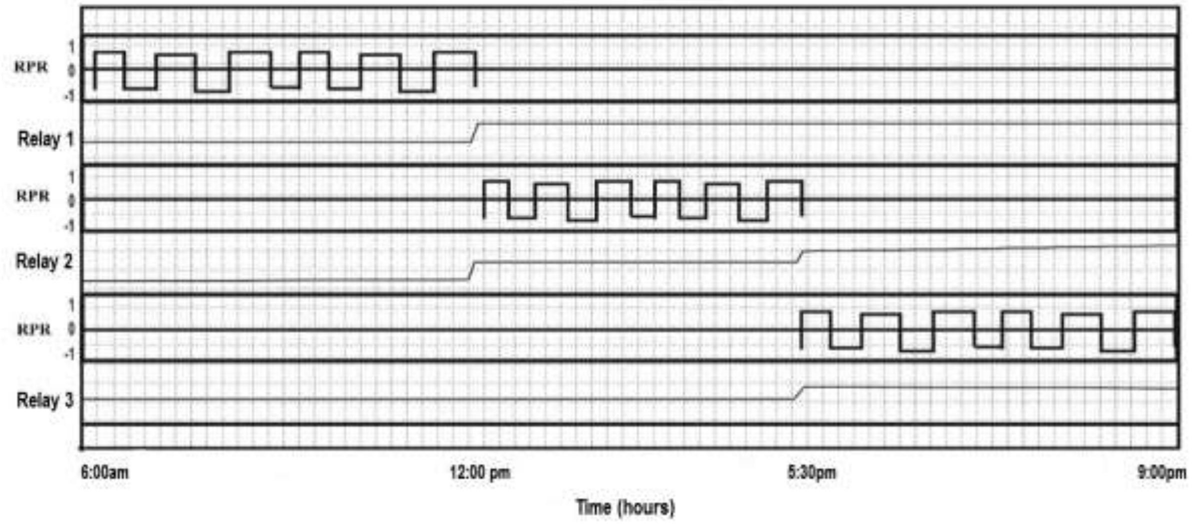

Fig. 6.3 RPR Action Via Smart RTU

6.5 Protection and Reduction in Intertripping Downtime

Differential protection relay for HV 22kV busbar at the MW-WTP POCs needs to be activated when heavy inrush or false differential current causes CT saturation under faults. Generated and calibrated analogue signals from the CTs are mapped to the corresponding smart RTU of the POC to activate a series of actions against these faults. (Fig. 6.4) simulation shows the current saturation and corresponding relay trip action at MW-WTP.

When a fault occurs or the CT reaches its saturation limits, protection relay will trip the correspondence feeder and POC CB automatically via the smart RTU for protection.

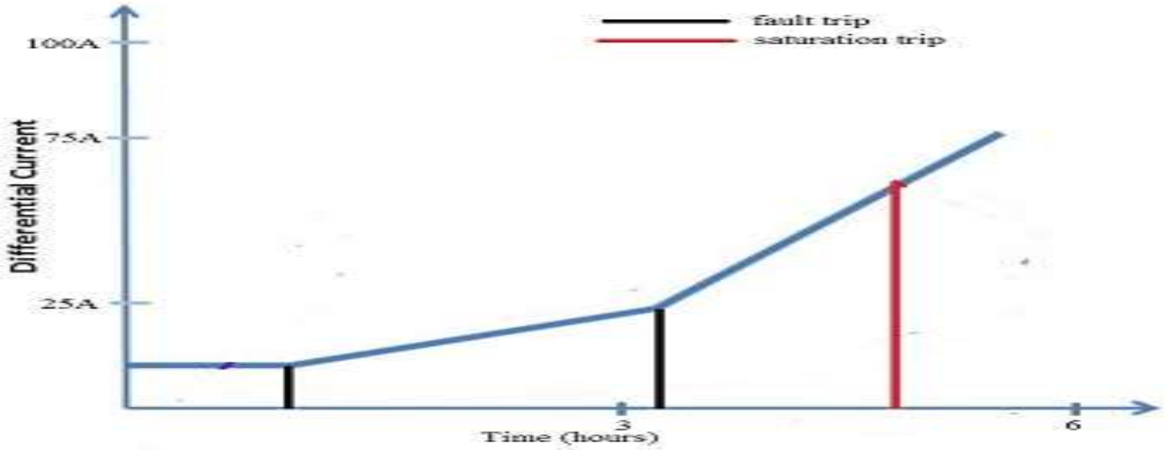

Fig. 6.4 Differential Current Protection Relay Action

(Fig. 6.5) results indicate that the busbar connected with MW-WTP has reduced intertripping downtime by 20% approx. at POCs with increasing current magnitudes using the smart RTU philosophy. It is achieved by provisioning FOCs to patch and communicate the telemetric signals between the smart RTUs of their respective substation.

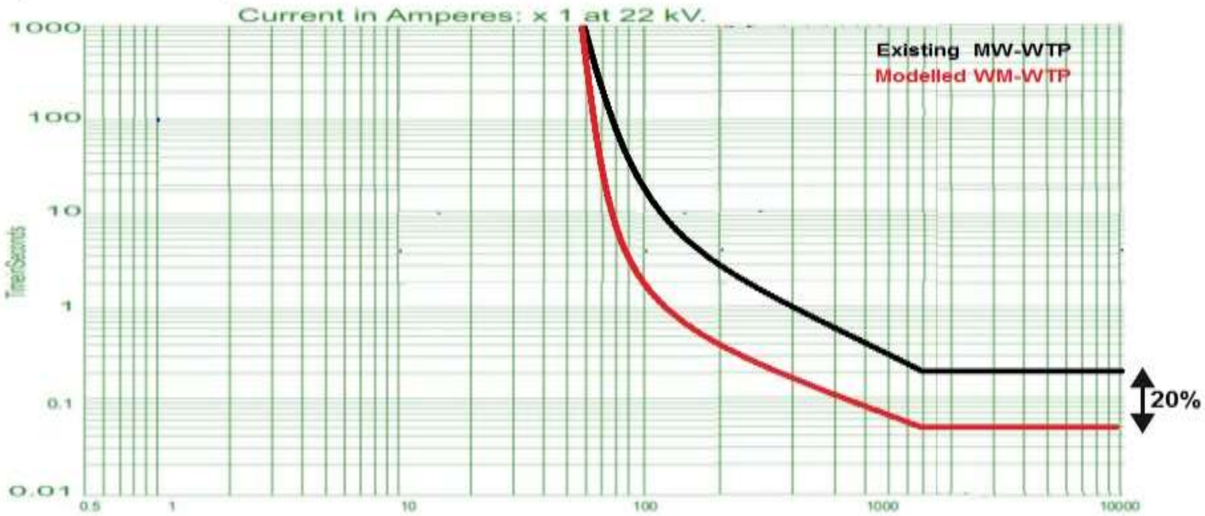

Fig. 6.5 Differential Current Protection Curves for MW-WTP

6.6 WWTP Power Generated Verses Reverse Power Generation

(Fig. 6.6) shows simulated results for MW-WTP generated power exported via POC1 and POC2 to the power company's zone substation. The smart RTUs at MW-WTP demonstrated optimised PMS by successfully switching power supplies at POCs. Reverse power decreases with increased power consumption and vice versa.

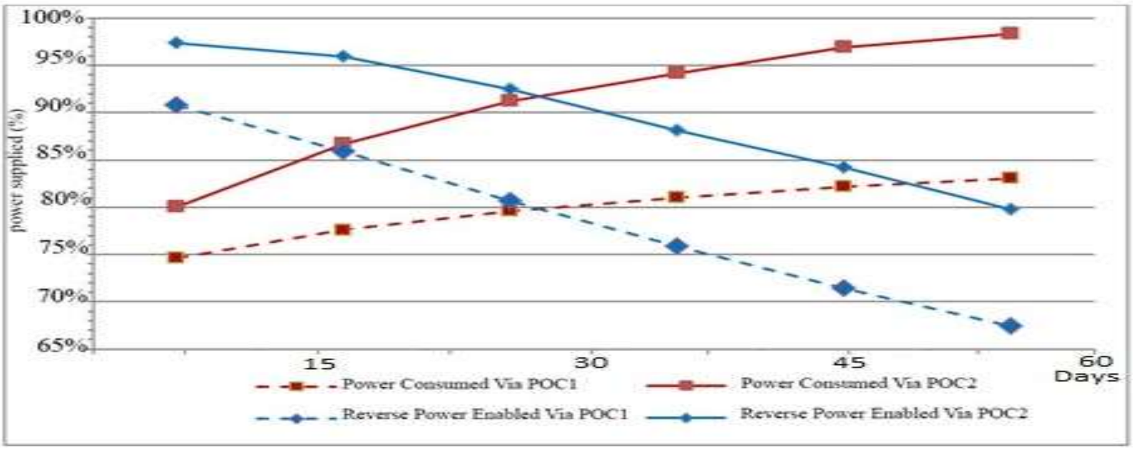

Fig. 6.6 Reverse Power Generation Evaluation Curves for MW-WTP

6.7 Modelled RTU

The modelled smart RTU resolved issues associated with old and existing infrastructure of MW-WTP by presenting a flexible solution to enable electricity cogeneration with efficient results. (Fig. 6.7) results indicates that efficiency increased approximately 25% of MW-WTP with modelled RTUs in terms of electricity cogeneration by effectively controlling and managing the scenarios and faults.

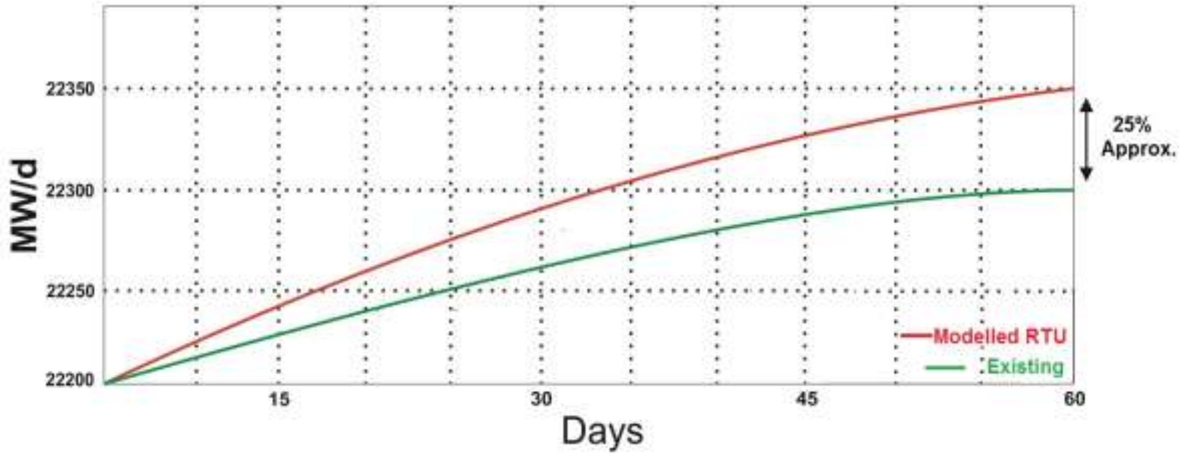

Fig. 6.7 MW-WTP Modelled RTU Efficiency

7. IMPACTS

7.1 Energy Efficiency

(Fig. 7.1) simulation results demonstrate optimised performance with significantly enhanced energy production by implementing the smart RTUs at MW-WTP. This efficient PMS consequently reduces load on the grids. It can also be observed that energy demand is usually less than the MW-WTP generation during summers by optimally utilising the onsite energy resources.

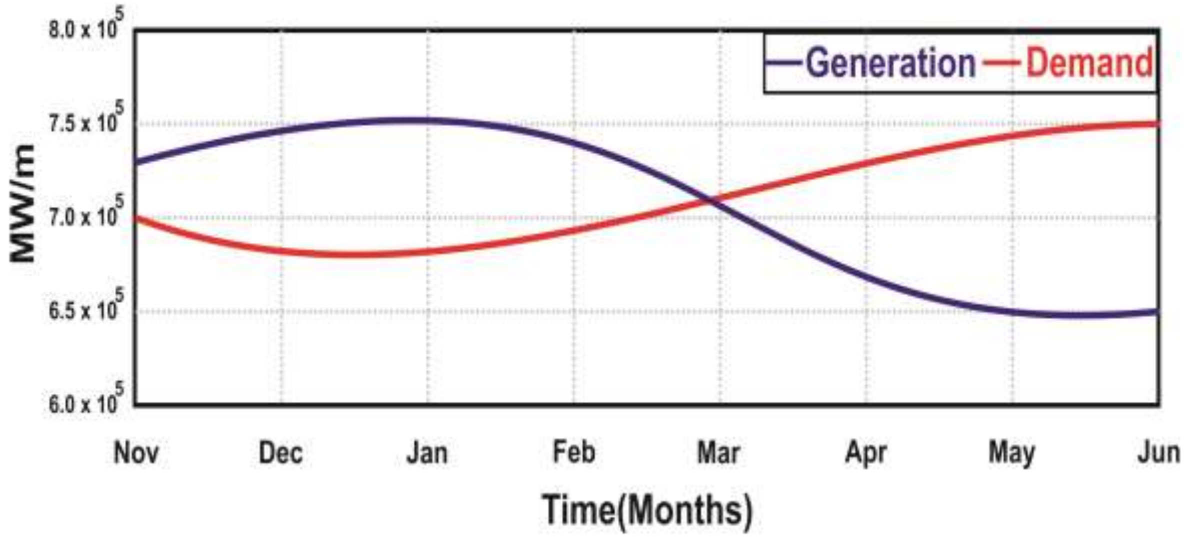

Fig. 7.1 MW-WTP Energy Production and Demand Curves

7.2 Renewable Energy

Wastewater is a renewable resource. The biogas produced through anaerobic digestion can be best utilised and managed for electricity cogeneration by implementing the smart RTU philosophy. Water treatment gives some other by products, which helps the recycling processes [26,27]. The proposed research provides a perfect platform to effectively control, monitor, and best utilise all of those renewable energy processes.

7.3 Environmental Impact

Wastewater treatment reduces waterborne diseases and keeps the ocean clean. The proposed research helps reduce GHG emissions and bad odor around the WWTP vicinity. It was noted at MW-WTP during the course of this research that by controlling and utilising the biogas produced can prevent approximately 87000 tonnes of CO2 to enter into the atmosphere. SAS using smart RTUs also reduces heat emissions. Moreover, treated sludge is used as a soil-improving substance for agriculture and treated water can be used in many ways. (Fig. 7.2) simulations at MW-WTP show reduction of CO2 emissions, reducing environmental footprint.

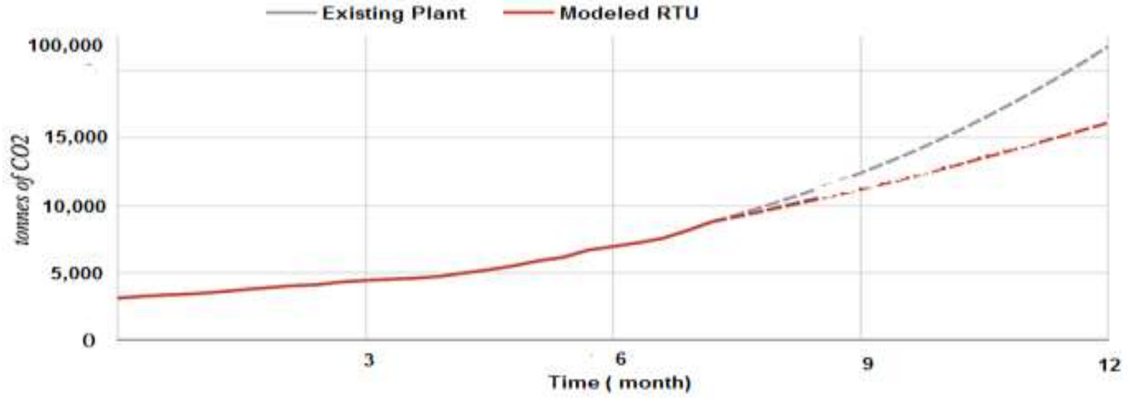

Fig. 7.2 SAS and Smart RTUs Reduces GHG Emissions at MW-WTP

7.4 OH&S

Automation of all interlocking, intertripping, switching and fault scenarios of MW-WTP has minimised the HV operator`s interaction with equipment, increasing OH&S standards. It provides a “one stop” for WWTP operators to determine faults and make corrective actions accordingly as per the plant`s design philosophy and O&M procedures. Reduced intertripping downtime has also improved safety of the power network during electricity cogeneration.

7.5 Easy to Implement on Existing and Old Infrastructure

Proposed modelled RTUs can easily be implemented on existing or old infrastructure at MW-WTP through minor modifications and minimum investment. They can be installed at various POCs, where smart metering and electricity cogeneration needs to be implemented, are easy to wire, maintain, and provides a stand-alone and safe point of control. Effective PMS and SAS can be achieved by implementing the smart RTUs at any WWTP or site where renewable resource is available.

7.6 Financial

Financial Savings are achieved in three ways. Reduction in power bills, man-hours required to operate and maintain WWTPs and by increasing the life of substations without replacing the existing switchgears in the POCs or commissioning new substations to manage the demand load. The research provides optimum utilisation of biogas and waste energy. (Fig. 7.3) simulation shows financial savings at MW-WTP. Considering maximum demand load and energy production at MW-WTP with failsafe and redundant power supply – PMS is more efficient using the modelled RTUs and serves an average saving of 0.65 million AUD over six months**.**

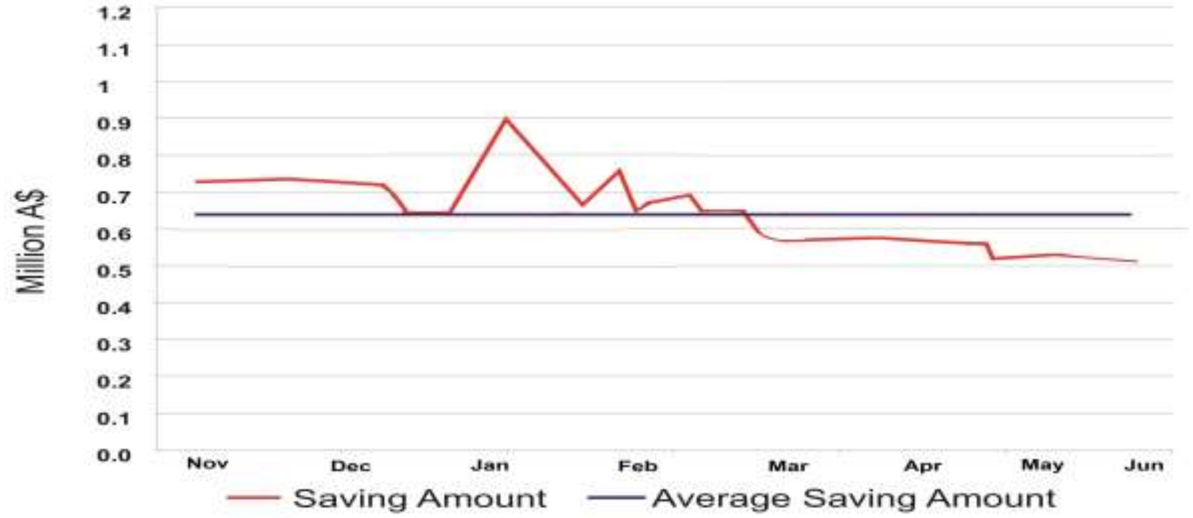

Fig. 7.3 Average Energy Saving Using Smart RTUs

CONCLUSION

This research shows the potentiality of anaerobic digestion for WWTP biogas production has successfully addressed the energy intensive demand and has made electricity cogeneration economically viable. Implementing smart RTUs and improving the mapping philosophy of telemetric signals functionality has considerably enhanced the safety of existing WWTPs equipment during cogeneration. This has effectively added the required communication between the zone and distribution substations, which the old/existing infrastructure lacked. Not only HV/LV redundancy was achieved, but also different layers of OSI protection were added to WWTP through an automated intertripping and interlocking mechanism, ensuring a failsafe and reliable multi-directional power flow with minimum losses. Sections of WWTP requiring maintenance or upgrade works can be isolated without affecting power supplies to other segments of the plant. OH&S standards are improved by minimising HV operator`s interaction equipment. Financial savings by implementing the smart RTUs on existing infrastructure without any expensive upgrades to the switchgear and the grids are massive. With the world moving towards renewable resources, it is important to implement such plans on sites that produce waste energy.

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