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Real-Time Condition Monitoring for Small Power Systems

RISHABH YADAV[1], VISHAL V. MEHTRE[2]

[1] *Student, Department of Electrical Engineering, Bharati Vidyapeeth University, Bharati Vidyapeeth (Deemed to be University), College of Engineering, Pune, Maharashtra, India*

[2] *Assistant Professor, Department of Electrical Engineering, Bharati Vidyapeeth University, Bharati Vidyapeeth (Deemed to be University), College of Engineering, Pune, Maharashtra, India*

Abstract- Power system components such as Power Generators, transformers, and transmission line are critical, capital-intensive assets. These components need to be extremely reliable. However, many generators and transformers have already exceeded their design life. Extending the useful life of the power system components is now possible due to advances in measurement, monitoring and communication technology, and high processing power available in today's computers. Power transmission lines encounter environmental risks such as high wind or tornados and lightning strikes. It is therefore of paramount importance to continuously monitor the condition, or health, of the power system to deliver uninterrupted power to the consumers, at competitive cost.

Indexed Terms- Real Time, Condition Monitoring (CM).

I. INTRODUCTION

smart grid is a class of technology that modernizes the utility delivery systems, using computer based remote control and automation. Great strides in two-way communication technology and computer processing have made it possible to implement smart grid technology in reliable manner.

Real-Time Condition Monitoring, or Smart Monitoring & Diagnostics, is essentially maintenance of equipment and utilities based on condition, or health of the equipment. Various sensors are used to monitor condition and operation of equipment used from generation all the way to the consumers. The information obtained is then transmitted, processed and used in diagnosis of equipment health. Operation and maintenance of equipment is determined based on collected data.

Today Condition based Monitoring (CBM) is only done for critical equipments. It is not extended to other parts of the power network. Condition of large consumer loads need monitoring too.

Condition monitoring related problems are transformer insulation breakdown, stator winding insulation breakdown, rotor vibrations, winding hotspots, solar panel thermal cracking, overheating of transmission lines among others. These problems reduce equipment lifetime and compromise the reliability of the power system.

With real-time condition monitoring, catastrophic equipment failure can be prevented, frequency of preventive maintenance can be reduced as well as operating costs and it improves the efficiency and reliability of the system.

II. PRESENT TRENDS IN CM AND SENSORS

There are many parameters that can determine the health of power system components but when it comes to real-time monitoring, the parameters of high-risk priority should be considered. The critical parameters to be monitored in the components of power system and respective sensors are tabled below:

TABLE I
CRITICAL PARAMETERS AND SENSORS

Equipment	Component	Critical Parameters	Sensors
	Rotor	Vibration	Accelerometer
	Rotor bearing	Temperature	Therma Watch

Turbo-generator/ Motors			Thermocouple
	Gear box	Temperature	RTD
			Therma Watch
			Generator Condition Monitor
	Stator winding	Temperature	Condition Monitors
			RTD
			Thermocouple
Wind Turbine	Rotor Blades	Vibration	Optical Fibre Bragg Gratings (FBG)
	Induction Generator	Vibration	Accelerometers
		Temperature	RTD
			Thermocouple
	Gearbox	Vibration of gear bearing	Accelerometers
		Temperature	RTD
			Thermocouple
			Therma Watch
			Infrared Thermo-graphic cameras
			Passive Electromagnetic Resonators
			Passive Dielectric Resonators
			Oil Temperature Sensors
			Therma Watch
			RTD

A. *Turbo Generators Condition Monitoring*

End Winding Vibration: Movement of stator windings has been clearly linked to erosion of semi-conductive layer, abrasion of insulation and packing, increased partial discharges and ultimately generator failure. It is widely known that the coils and end-windings are subject to strong electromagnetic forces at twice the synchronous frequency. The end-windings experience significant vibration as a result of these forces, which eventually lead to a weakened blocking and bracing system, insulation cracks, cooling leaks and potentially short-circuits [3].

In recent years, fibre optic accelerometers have been developed to monitor end-winding vibration since this is the only type of accelerometer that can be safely coupled to the end-windings themselves.

The accelerometer operates on a method of light reflection from a mirror mounted at the end of a cantilever beam inside the accelerometer head. The rate of change in the intensity of deflected light detected by the optoelectronics of the integral feedthrough/signal conditioner is deciphered to determine the proportional acceleration. The output of the FOA-100 signal conditioner is 100 mV/g which is a standard for general purpose accelerometers. Therefore, this accelerometer is fully compatible with any common vibration analyzer or on-line vibration monitor [1] [2].

Temperature rise in the stator is a good indicator of problems with core or windings usually caused by cooling deficiencies, insulation deterioration, electrical Faults, uneven air gap. Distributed sensing devices (ThermaWatch) for thermal mapping of stator windings can be used to identify these problems in turbo generators. [24]

B. *Photovoltaic Solar System Condition Monitoring*

Photovoltaic cells convert sunlight into electrical energy, and are commonly known as solar cells. Photovoltaics can literally be translated as light-electricity, and they take advantage of the photoelectric effect to produce that electricity. These cells are the building blocks of all photovoltaic solar systems because of that property. [5]

The performance of Solar cells is dependent on its health condition. [3] When individual cells become damaged, due to defects in manufacturing or external incidents, the power output lowers and efficiency drops. These defects lead Hotspots. Other causes of Hotspots are interconnection failure, failed bypass diodes, high contact resistance at the busbars of the cells and partial shading as a result of accumulation of dirt and moisture [3]-[5]. When these problems occurs a cell of a string becomes negatively biased and instead of producing electrical energy it produces heat energy [5] [8]. Without condition monitoring the condition of the cells can never be known until the cells fails completely.

Also the conditions of PV converter need to be monitored. The major failure causes of photovoltaic converters are temperature shifts resulting in solder and bond-wire fatigues of the IGBT power modules. In order to predict its remaining life time, significant system-parameters such as temperature, electric current and voltage have to be measured [19].

The following methods are currently used for condition monitoring of Solar Panels:

1).Output Testing: The output of one module must be compared with that of another under the same field operating to conditions. One of the best methods to check module output functionality is to compare the voltage of one module to thatof another. A difference of greater than 20 percent or more will indicate a malfunctioning module. However, the output of a PV module is a function of sunlight and prevailing temperature conditions, and as such, electrical output can fluctuate from one extreme to another [4].

*2).Infrared Thermography***:** This has the ability to see the heat differential between solar cells and can be used to determine whether any of those cells are damaged or defective. For large arrays of solar cells, thermographic images of solar panel are taken from a Helicopter, while for small arrays of solar cells; thermographic images are taken by just walking around them [5].

*3).Indirect Measurement technique***:** it is not possible to measure the IGBT-chip-temperature directly. Therefore the indirect measurement technique was introduced. The collector- emitter-voltage V_{CE} is proportional to the chip temperature.

Corrective action may be introduced when the temperature limit is exceeded [19].

C. Wind Turbine Condition Monitoring

A wind turbine is used to generate electricity from the kinetic power of wind. There are basically two types of Wind turbines namely [9]:

Vertical Axis: This has its blades rotating on an axis perpendicular to the ground.

Horizontal Axis: Its blades rotate on an axis parallel to ground.

However, very few vertical axis machines are available commercially [9]. For this reason we will be considered real time condition monitoring of a Horizontal Axis Wind Turbine.

The horizontal Axis Wind Turbine is of two design types [9]:

1) Upwind Turbines: These turbines are designed to operate in an upward mode with the blades upwind to the tower.

2) Down-Wind Turbines: These turbines operate in a downwind mode that wind passes the tower before striking the blades.

Condition Monitoring of Wind turbine is necessary due to vibrations of the rotor blades as a result of imbalance, generator and gearbox and temperature rise within the nacelle of the wind turbine [10] [11]. The authors in [12] and [13] give us a priority list of components of a wind turbine to be monitored, which are Rotor blades, Gearbox and Induction Generator (Stator Windings). The impact and failure risk of these components are very high. [11]. Gearbox failure has been a problem from the beginning. Researchers from relevant disciplines worked together to address the issues and establish gearbox standards, but the gearbox failure rate is still high and the failure rate is expensive [13].

The two main causes of vibration are [11]:

1) *Mass imbalance*: This is as a result of an inhomogeneous mass distribution across the blades due to manufacturing inaccuracies.
2) *Aerodynamic imbalance:* This is as a result of an uneven load on the blades, due for example to an uneven pitch angle between the three blades.

Sensors used in monitoring Vibrations of Wind Turbines [11]:

1) Optical Fibre Bragg Gratings: In order to monitor the blades of a wind turbine at real time, optical fibre Bragg gratings are installed in the blades. This is the only available method for monitoring rotor blades of wind turbines. Part of the outputs related to vibration of the rotor is Mass and Aerodynamic imbalance of device. With this outputs it will be easy for the control personnel to detect any vibration on the rotor blades.

2) Accelerometers: They are fitted to the turbine – they are situated on the gear bearing in the gearbox and within the stator windings of the generator.

Sensors used in monitoring Temperature of Wind Turbines [11]: Resistance Temperature Detector (RTD) and Thermocouples

D. Transformer Condition Monitoring

Loading capability of power transformers is limited mainly by winding temperature. The temperature of the winding is not uniform and the real limiting factor is actually the hottest section of the winding commonly called winding hot spot. This hot spot area is located somewhere toward the top of the transformer, and not accessible for direct measurement with conventional methods [14].

The aging of transformers is directly linked to the temperature of the winding insulation. [9] [14]. The windings of these transformers come in different classes.

TABLE II
HIGHEST TEMPERATURE VALUES AT INTENDED USE [20]

Components	Temperature °C
Thermal class A	100
Thermal class B	115
Thermal class E	120
Thermal class F	140
Thermal class H	165

From [15] the maximum temperature rise values of transformers are usually 80° C, 115° C, or 150° C. These values are usually based on a maximum ambient temperature of 40° C or 30° C.

During the course of this project we made enquires on the critical parameters that should be monitored in a transformer. Enwin Utilities stated categorically that oil and winding temperature are the main parameters to be monitored in a transformer. The authors in [7] stated clearly that Insulation is the major component, which plays an important role in the life expectancy of the transformer. To determine the performance and aging of the asset, insulation behavior is a main indicator.

Most of the transformers in a system, around the world are exceeding their designed life. For this reason real time monitoring of the oil and winding temperature is of essence.

E. Transmission line Condition Monitoring

Power lines the mediums (conductor) by which electricity generated and transmitted at High voltage via various transformers (from step-up to step-down transformers) to the consumers at Low voltage. There are two types of transmission lines: Overhead and Underground lines. For this paper will be considering real time condition monitoring for overhead lines since it's a small power system that is in view.

The Transmission Network is classified into the following sub-systems [16]:

1) *Transmission System*: This interconnects all major generating stations and main load centers in the system. It forms the backbone of the integrated power system and operates at the highest voltage levels (230 kV and above).
2) *Sub-transmission System*: This transmits power in smaller quantities from the transmission sub-stations to the distribution substations.
3) *Distribution System*: This represents the final stage in the transfer of power to the individual customers.

There is an impending need to equip the age old transmission line infrastructure with a high-performance data communication network that supports future operational requirements like real-time monitoring and control necessary for smart grid integration [10]. The main condition to monitor on a transmission line is the temperature rise of the conductor.

There are various types of conductors but Aluminum Conductor Steel Reinforced (ACSR) is mostly used.
Methods of monitoring temperature of a Transmission Line:

1) Estimation using weather conditions: Today the Temperature of overhead line monitored by collecting this information through hazardous, expensive, and time- consuming field inspections but utility providers have tried to minimize these inspections by applying intricate formulas to estimate temperature, based on weather conditions around a line and the current load. This method includes large tolerances to make up for the lack of direct measurement, and companies know they are imposing limits on electrical transmission that are well below the actual thermal limitations of the lines. Without much more detailed input, these generous margins of error represent the only safe way to proceed [17].

3) *RTTR Calculation Engine:* This calculates temperature conditions at the core of the conductor Mathematical thermal model of the transmission system Ampacity calculation using standards [18].
4) *Passive Electromagnetic Resonators*: This is a recent invention. This device can be attached onto each overhead- line. The metal in the line will expand as it heats up, and the resonating cavity dimensions of the sensor will likewise expand, providing a change in signal that can be calibrated to the change in temperature. Using this method will reduce the margins of errors encountered using the method above [17].
5) *Passive Dielectric Resonator:* Authors of [18] are still working on this proposed sensor. This resonator uses a particular type of ceramic material that's very sensitive to temperature variations.

F. Consumer Load Condition Monitoring

Effect of unscheduled variations in consumer demand makes significant impact on power grid. When large consumers overload the system, or sustain a fault, the disturbances are felt by the power grid and they are challenging to manage. Therefore, a way of sending a message to the large consumers of potential overloads, or faults, is proposed. Consumers are expected to adjust their load demands based on these messages. Alternatively, the nearest control station may be authorized by the consumer to adjust the power supply. Discussions with local utility providers revealed a need to install smart meters on power distribution transformers, to monitor the power flow and to detect power theft.

III. SIMULINK SIMULATION/RESULTS

Our Simulink model (shown below) presents an arbitrary power system that incorporates a convention power generator,

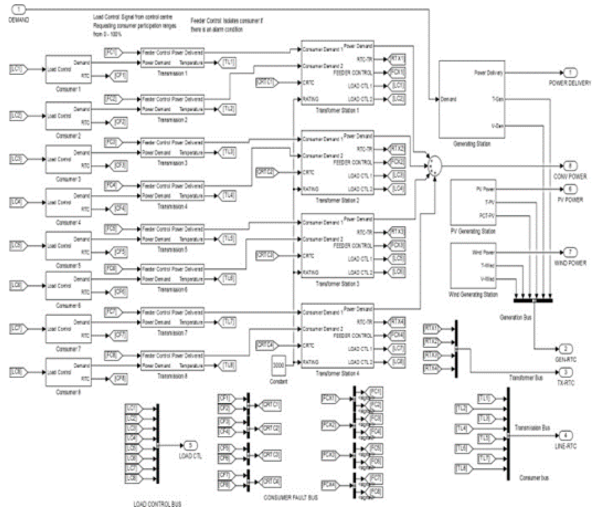

Fig.1. Real-time Condition Monitoring Power System Model.

a wind turbine unit and solar panel (PV) unit. It features four transformer stations, eight sets of power transmission lines and eight consumer units. There is one control and distribution centre that monitors and controls overall power flow and each transformer station incorporates a monitoring and control station that manages the flow of power delivered by respective transformer station.

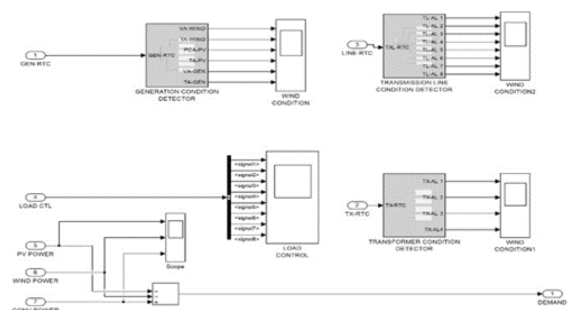

Fig.2. Monitoring and Control Station Model

A. Control Centre

Model of the monitoring and control station incorporates monitoring subsystems for power generation, transmission lines, transformer stations and a load control subsystem that monitors overall load and sends power management recommendations over to the consumers.

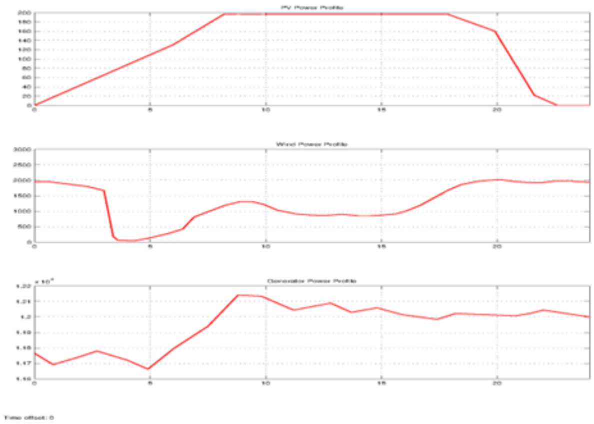

Fig.3. Power Generation Profile for Generator, Solar Panel and Wind turbine.

B. Power Generation Profile

Power generation profile incorporates generation profile of wind and solar panel systems. Wind generating system produces arbitrary power whereas solar system generates power depending upon time of day. Overall power generation by the convention power generating station is then computed by deducting wind and solar power from consumer demand.

C. Proposed (Ideal) consumer model

Ideal consumer generates an arbitrary power demand, based on time of the day. Manual switches in the Simulink model may be flipped to simulate overload condition, faults and managed/unmanaged load conditions. Controlled load subsystem takes into account the ambient temperature and computes maximum allowable load on the machines. Further, a load control signal received from Control station may be used to adjust the power demand.

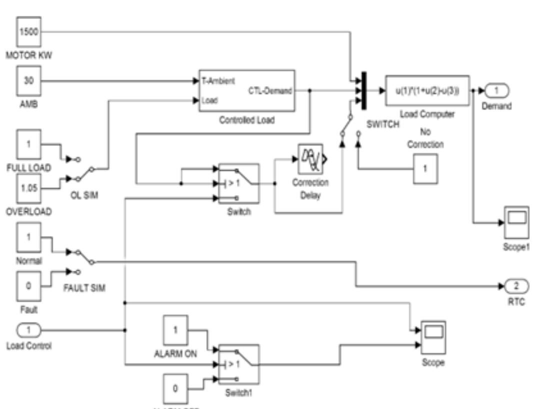

Fig.4. Proposed Ideal Consumer Model.

D. Load Control Technique

Assuming a machine with Class F insulation, load temperature characteristics are used to derive maximum load under prevailing ambient temperature.

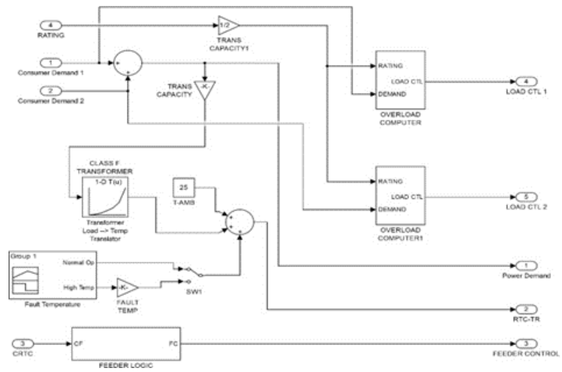

Fig.5. Load Control Model.

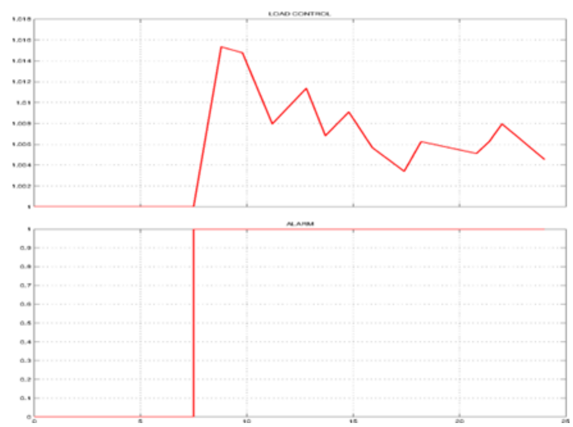

Fig.6.Graph showing load monitoring profile under overload conditions shows clearly that an alarm is generated at the control centre and the message is transmitted to the consumer to take necessary action.

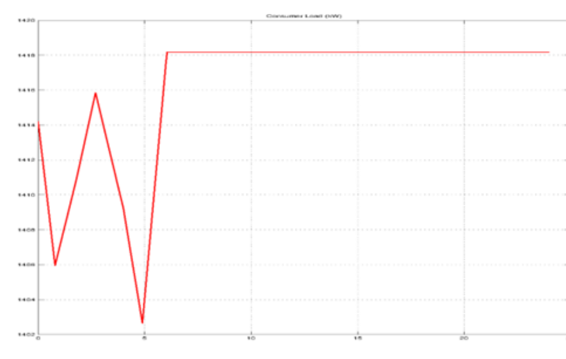

Fig.7. Load control characteristics indicate the reduced power demand by the consumer, as suggested by the control centre.

E. Transmission Line Model

Transmission line model takes into account the line temperature and from the load temperature characteristics and computes maximum permissible load under the ambient temperature conditions. It has ability to cut-off consumer power demand if a fault condition is detected.

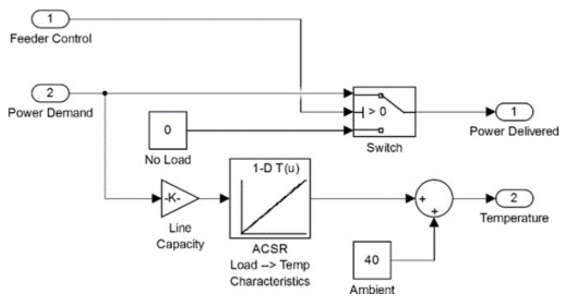

Fig.8. Transmission Line Model.

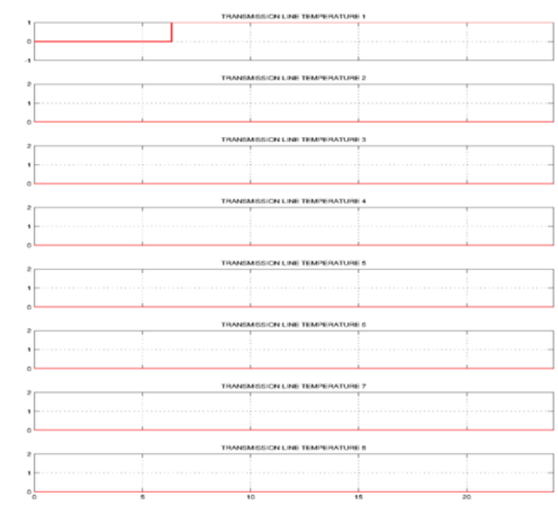

Fig.9. Transmission Line Alarms: Transmission 1's maximum temperature (100°C)[21] exceeded.

F. Transformer Model

Transformer station model consists of a load computer, a load-temperature characteristics computer and feeder logic. Load computer compares the power demand with the capacity of the transformers and generates load control signals that are transmitted to the consumers. A load-temperature characteristic for a transformer with class F insulation was used to compute maximum permissible power consumption under ambient condition and to transmit the alarm signals to the control centre. An arbitrary fault temperature simulates winding and insulation hotspot conditions.

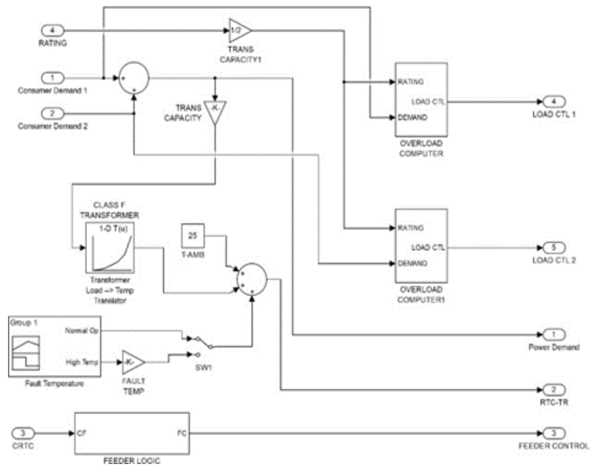

Fig.10. Transformer Model

G. Generation Station Model

A Simulink model for conventional power generation station simulates a Class F insulation power generator, with arbitrary temperature and vibration patterns to simulate respective fault conditions [23] [25]. These fault conditions are transmitted to the control centre to generate alarm signals. The generator model computes temperature and vibration signals based on fault conditions and power demand.

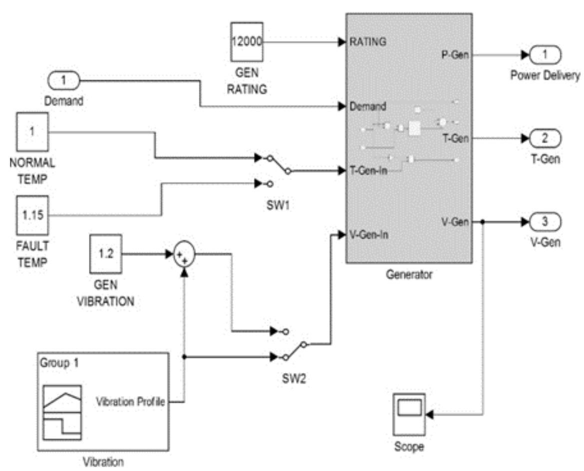

Fig.11. Generator Subsystem

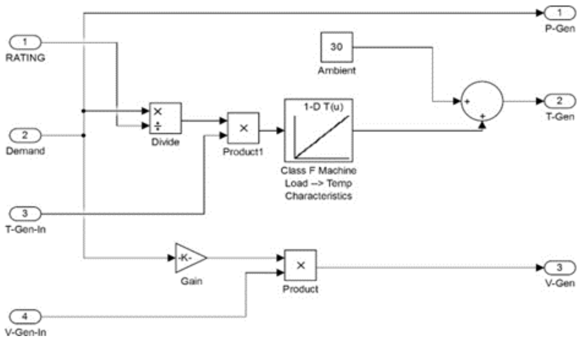

Fig.12. Turbo-Generator Model

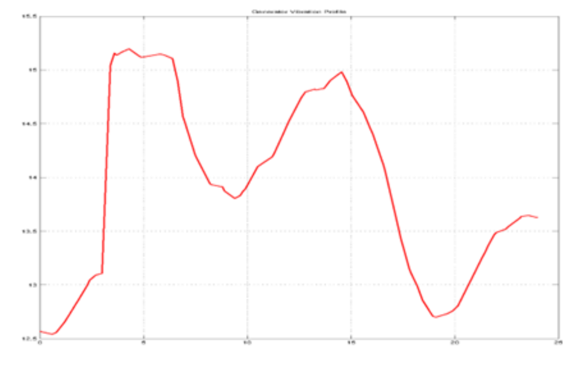

Fig.13. Vibration profile with a limit of 14µm peak - to-peak [23]

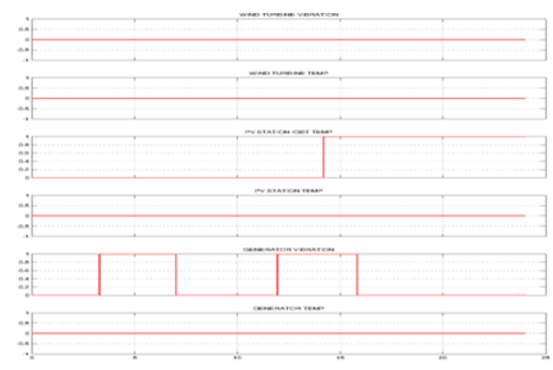

Fig.14. Trace 5 showing vibration alarms of the Generator

H. Wind Turbine Model

Wind Turbine model produces wind power based on an arbitrary wind speed patern. Vibration and gearbox temperature are modeled to be proportional to load [22].

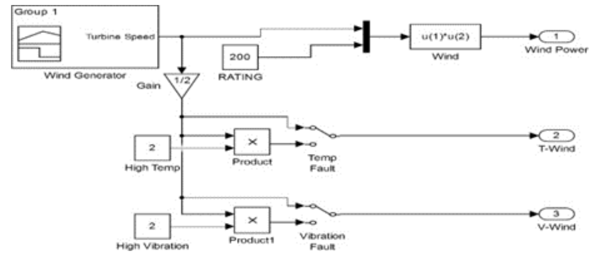

Fig.15. Wind turbine model [23]

In such a scenario, a video camera may be installed in front of the alarm and monitoring panel, and using computer vision and dynamic image processing techniques, the health parameters may be digitized and transmitted over communication media. This technique is not in use, however, is worth exploring.

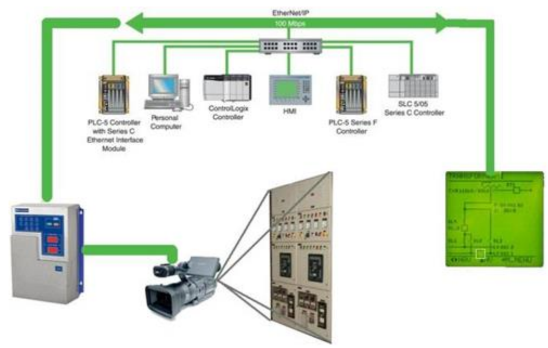

Fig.21. Block diagram for Retrofit Technique for Older Equipment.

CONCLUSION

The health of power system components are of vital importance if the system is to maintain reliable operation of the system. Critical health parameters generate alarms to warn operators of equipment health concerns. Knowledge of the component health allows the operators to schedule timely maintenance. Maintenance engineers can then address the specific problem detected.

It's important that consumer demand is managed to prevent system overload. This has adverse effect on temperature rise in transformers and transmission lines. Intelligent power control will help consumers to manage their load

Lastly, the government and regulatory bodies must work together to stipulate and standardize health parameter metric and setup regulatory policies to ensure that real-time condition monitoring is implemented in our power system and allow researchers access to health parameter data of the various components that make up a power system for further research on how to improve and develop better means of monitoring the conditions of these components.

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