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Mathematical modeling and simulation of energy management in smart grid

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Abstract

A Smart Grid (SG) or Intelligent Grid is the solution for modernizing the electric power system and infrastructure to create a smarter and more reliable electricity grid. The synergies of Electric Vehicles (EVs) and Renewable sources of energy in a Smart Grid play an important role in promoting energy savings and reducing emissions. This paper portrays a strategy for Energy Management (EM) to maintain energy sustainability in the environment of smart grids. The system is modeled by considering solar source, loads, energy storages and utility grid. The different operating modes of Energy Management System is presented. The simulation outcomes emphasize the efficacy of the proposed management strategy and the possibility of Electric Vehicle storage system in enhancing the renewable exploration.

Keywords: Electric vehicles, energy management, smart grids

1. Introduction

Electric Power is considered as one of the significant and most vital technologies in the 20th century giving rise to the rapid industrialization and globalization. A Smart Grid (SG) is an electricity transmission and distribution network that incorporates digital and other advanced Information and Communication Technologies (ICTs) for sensing, monitoring, communicating and managing the energy flow. It takes online decisions from all generation sources to meet the varying electricity demands of end users. Smart Grids oversees the generation, transmission and distribution asset's real time capabilities [1]. It enables the power system operators to manage the most efficient way of controlling the balance between generation and load demands. The use of storage devices is essential due to the intermittent nature of the solar, wind powers and also due to sudden variations in the power produced by intermittent sources.

Electric Vehicles (EVs) are becoming popular due to their potential to reduce fuel consumption, emissions and ability to increase Renewable Energy Sources (RESs) penetration into the transportation sector [1]. The integration of the electrical mobility in a smart grid should be considered in a complex system characterized by several factors, mainly including the generation of electricity from renewable resources distributed across the territory, the energy storage systems and the management tools that bind together the various elements.

2. Representation of Smart Grids in Smart Cities

Smart Grids play an important role for the sustainable use of energy in Smart Cities [2]. Smart grid helps the consumers to be energy suppliers known as prosumers. It allows the two-way flow of information and electricity between consumers and electric power companies. Smart cities are a logical extension of the concept of smart grids and the realization of smart cities is closely linked to the modernization process of traditional power system. The features of a Smart Grid include:

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- Increased use of digital information and control technology to enhance electrical grid reliability, safety, and efficiency.
- Dynamic grid and resource optimization with full cyber security.
- Deployment of distributed resources and generation, including renewable resources.
- Development and incorporation of demand response and demand-side management techniques.
- Application of “smart” technologies for metering, communications concerning grid operations and status, and distribution automation [2].
- Integration of advanced technologies for electricity storage, like Electric Vehicles (EVs).

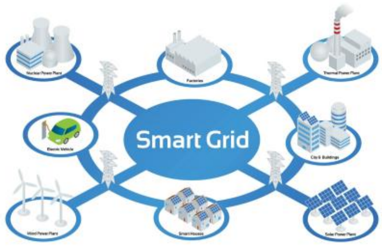

Fig. 1. Schematic smart grid

Thus, a smart grid sits at the heart of the smart city, which cannot fully exist without it as shown in Fig. 1. Faced with the need for integration of renewable resources, the energy management algorithm is a great solution for making an efficient decision on power delivery.

3. Energy Management Technologies in Smart Grid

These are designed to monitor the quality of power and control the power system distribution. Some of the advanced technologies are [3]:

3.1. Zigbee wireless network

ZigBee is the key technology that enables home energy management products. It is a wireless networking standard based on ultra low-power IEEE 802.15.4 that has emerged as a key to robust, reliable and secure Home Area Network (HAN) deployments.

3.2. Advanced Metering Infrastructure (AMI)

AMI technology enables utilities to perform meter readings on a regular basis and to keep track of interruptions of outages and performance of the distribution system. Automatic Meter Reading (AMR) enables utilities to have information about a particular location and the ability to access information quickly at any time of the day.

3.3. ZigBee-based AMI/HAN deployments

With the introduction of the ZigBee Smart Energy (SE) Profile, the ZigBee standard, which is governed by the ZigBee Alliance, has recently taken another major step forward for AMI / HAN energy management. The SE profile defines the standard behaviors of Home Area Netwrok (HAN) devices that are secure and easy to use.

3.4. Self-Healing

The grid's self-healing capability makes the grid intelligent and smart. This requires effective grid monitoring, analysis and control. The Supervisory Control and Data Acquisition (SCADA) is used for management in the smart grid as well as data acquisition that can be used in the development of energy management systems [4]. SCADA systems work by the transmission of data between Remote Terminal Units (RTU's) or Programmable Logic Controllers (PLC's) to a central host computer.

This paper focuses on grid integration and coordination of renewable energy resources, energy storage systems and electric vehicles by using an Energy Management Strategy (EMS) in Smart Grid environment. In this topology, the PV array is working in MPPT mode and it is interfaced with the DC bus by a DC/DC boost converter. Here, two energy storage systems are considered. One is the Stationary Battery Bank (SBB) and other is the Electric Vehicle Battery (EVB) in parking mode. These batteries use bidirectional DC/DC converter to control the charging and discharging processes. To interconnect DC and AC networks, a centralized inverter is installed. DC load block generally represents the loads that are connecting at the DC bus. There are also AC loads consuming power at the AC bus. Depending on priority of loads and batteries State of Charge (SOC) the energy is transferred among the sources, load and grid.

4. Modeled System Configuration

The modeled system consists of a renewable energy source, two energy storages, inverter, bidirectional DC-DC converter, AC load, DC load and utility grid which are interconnected with AC and DC buses and LC filter to reduce harmonics. Fig. 2 represents the SG working with various applications.

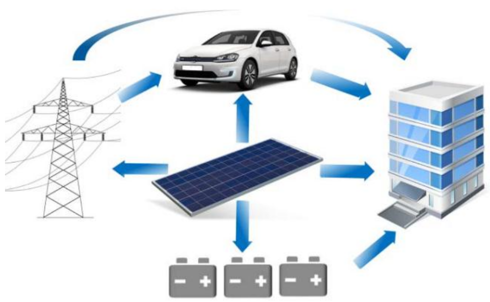

Fig. 2. Schematic of SG integrated RES and EV

4.1. Renewable Energy System (RES)

In this paper, Solar PV system is considered as a RES. An ideal current source, a diode representing the p-n semiconductor junction, internal shunt resistance R_p, and internal series resistance R_s can represent a standard design of a solar cell as shown in Fig. 3.

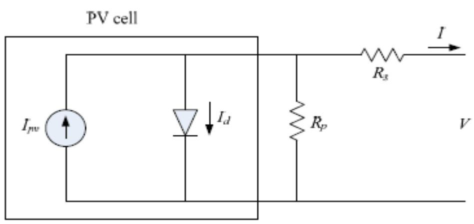

Fig. 3. Equivalent circuit of a PV cell

The basic equation that describes the I-V characteristics of a solar cell from the semiconductor theory is given by [5]:

$$I = I_{pv,cell} - I_{o,cell}\left[\exp\left(\frac{qV}{akT}\right) - 1\right] \tag{1}$$

The general expression for the current of solar cells is [5]:

$$I = I_{pv} - I_o\left[\exp\left(\frac{V + R_S I}{V_t a}\right) - 1\right] - \left(\frac{V + R_s I}{R_P}\right) \tag{2}$$

where,

I_{pv} is pv current of the array, $I_{pv}=I_{pv,cell}N_p$

I_o is pv current of the array, $I_o=I_{o,cell}N_p$

V_t is thermal voltage of the array, $V_t=N_s kT/q$

N_s is total number of pv in series

N_p is total number of pv in parallel

R_s is equivalent series resistance

R_p is equivalent parallel resistance

a is arbitrarily chosen. Usually $1 \leq a \leq 1.5$ and the choice depend on other parameter of I-V model

The light generated current of a solar cell is [5]:

$$I_{pv} = \left(I_{pv,n} + K_I \Delta_T\right)\frac{G}{G_n} \tag{3}$$

where,

$I_{pv,n}$ is light generated current at 25^0C and $1000W/m^2$

Δ_T is differences of actual and nominal temperatures

K_I is current coefficient

G is irradiation on the device surface

G_n is nominal irradiation

The diode saturation current, I_o and its temperature dependence can be expressed as [5]:

$$I_o = I_{o,n}\left(\frac{T_n}{T}\right)^3 \exp\left[\frac{qE_g}{ak}\left(\frac{1}{T_n} - \frac{1}{T}\right)\right] \tag{4}$$

where,

$I_{o,n}$ is the nominal saturation current given by:

$$I = \left[\frac{I_{sc,n}}{\exp\left(\frac{V_{oc,n}}{aV_{t,n}} - 1\right)}\right] \tag{5}$$

where,

E_g is the band gap energy of the semiconductor

$V_{t,n}$ is thermal voltage at nominal temperature, T_n

$V_{oc,n}$ is open-circuit voltage at nominal temperature

$I_{sc,n}$ is short-circuit current at nominal temperature

The PV array which is connected to the DC bus through a DC/DC boost converter converts solar energy into DC power. Indeed, due to nonlinear characteristics of PV panels and stochastic fluctuations of solar irradiance, a Maximum Power Point (MPP) is always available for each specific operating situation of a PV array. The proposed EMS uses the Perturb and Observe MPPT, which provides a V_{MPPT} reference voltage that will be tracked by the PV array to produce maximum power under different operating conditions.

4.2. Stationary Battery Bank energy system (SBB)

The SBB is designed as controlled voltage source connected in series with constant resistance as in Fig.

4. The open voltage source is calculated using a non-linear equation based on the battery's actual state of charge (SOC) defined as the remaining capacity of the battery expressed in percentage and affected by the temperature, battery life and discharge rate [6]. The SOC estimate is essential for battery management. A battery's SOC is defined as [6]:

$$SOC(t) = \frac{Q(t)}{Q_{nom}} \tag{6a}$$

$$SOC = 100\left(1 + \int \frac{I_{bat}\,dt}{Q}\right) \tag{6b}$$

where,

$Q(t)$ is the residual charge available

Q_{nom} is the nominal capacity given by the manufacture

I_{bat} is the battery charging current and

Q is the battery capacity.

The controlled voltage source is given as:

$$E = E_0 - K\frac{Q}{Q - \int i dt} i + A\exp(-B\int i dt) \tag{7}$$

where,

E_o is battery constant voltage

K is polarization voltage

Q is battery capacity

A is exponential voltage

B is exponential capacity

i is battery current

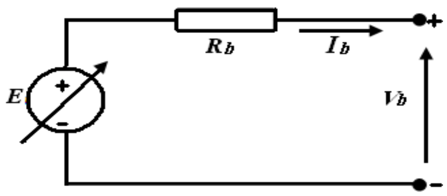

Fig. 4. A Generic Battery Model

The battery's energy limits are determined depending on SOC levels. Based upon the SOC, available power and demand, batteries are operated either in charging or discharging modes.

$$SOC_{SBB\_\min} \le SOC_{SBB} \le SOC_{SBB\_\max} \tag{8}$$

where,

SOC_{SBB_min} and SOC_{SBB_max} are the minimum and the maximum allowable states of SBB for the battery safety.

4.3. Electric vehicle battery energy system (EVB)

An Electric Vehicle (EV) is a type of vehicle powered by electric motors rather than using an Internal Combustion Engine (ICE), and the motor runs by using the power stored in specific batteries. The EV comprises of:

4.3.1. Battery model

An EV battery is designed as a controlled source of voltage and an internal resistance that changes with the flow of electrical power and load. In this paper, Lithium (Li)-ion battery is considered which comprises of more excellent performance characteristics such as longer life, high energy density, and more light weight [7]. The battery voltage tends to drop as the SOC decreases and the amount of current drawn from the battery increases.

$$SOC_{EVB\_\min} \le SOC_{EVB} \le SOC_{EVB\_\max} \tag{9}$$

where,

SOC_{EVB_min} and SOC_{EVB_max} are the minimum and the maximum allowable states of EVB.

4.3.2. Power Electronic Converters

4.3.2.1. Inverter

Inverter converts DC power, typically from a battery pack voltage, to alternating phases of power to drive electric motor. The two key performance measures are power capability and efficiency.

4.3.2.2. Bidirectional DC-DC converter

The DC-DC converter is used in EV as an interface circuit between battery pack and DC link Bus. It allows power flow from the high voltage to low voltage when acting as a buck converter while the power flow from the low voltage to high voltage requires the converter to act as a booster as in Fig. 5. As a result, the use of bidirectional DC-DC converter allows the use of multiple energy storage, and offers advantage of flexible DC-link voltages which can enhance system efficiency and reduce component sizing [8].

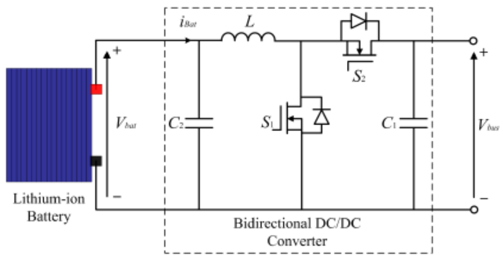

Fig. 5. Battery model of Lithium-ion connected to bidirectional DC-DC converter system

4.3.2.3. Rectifier

The rectifier converts AC from electric grid to DC to charge on-board battery pack. Also, during regenerative stage in EV, when braking or slowing the vehicle down, a considerable amount of energy is generated which needs to be stored in the battery pack. Currently, the converter acts as a rectifier to recharge the battery.

4.4. Electric motor

A Permanent Magnet Synchronous Machine (PMSM) motor is one of the well-suited motors for an electric vehicle power system due to its high performance, sufficient acceleration ability, and strong torque. A PI controller is designed to control speed and torque of a motor, and a decoupling PI controller with feed-forward controller is designed to control d and q axes' currents. The governing equations for mathematic model of the PMSM motor are as follows [9]:

$$v_d = R_s i_d + L_d i_d - \varpi_r L_q i_q \tag{10a}$$

$$v_q = R_s i_q + L_q i_q + \varpi_r (L_d i_d + \Lambda_m) \tag{10b}$$

$$T_c = \left(\frac{3}{4}P\right)\left[\left(L_d - L_q\right) i_d i_q + \Lambda_m i_q\right] \tag{10c}$$

where,

ω_r is the electrical angular velocity of a rotor,

P is the number of poles, and

R_s, L_d, L_q, and Λ_m are resistance, d-axis inductance, q-axis inductance, and phase flux linkage respectively.

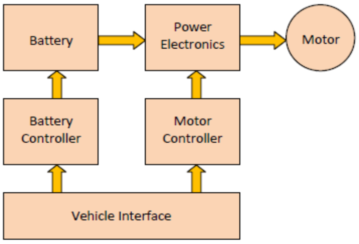

Fig. 6. EV Structure

4.5. Vehicle dynamics

The vehicle dynamics represent the motion influence on the overall system given as in Fig. 6. The energy transformed to the vehicle wheel is converted once more to energy for displacement. The tyre's dynamics represent the force applied to the ground. Accordingly, the overall consumed energy at the tire can be obtained from the time integral of the power as [9]:

$$E_{wheel} = \int_0^t P_{wheel}(t)dt \tag{11a}$$

For the electric powertrain that transmits the instantaneous tractive power to the wheels, P_{wheel} to sustain a certain speed level, road grade and acceleration along with displacement is determined by the tractive force and vehicle speed as:

$$P_{wheel} = \int_0^t v(t)F_t(t)dt \tag{11b}$$

where,

v is the vehicle's speed and

F_t is transited traction force by the powertrain to the wheels.

Further, the energy stored in the batteries of the vehicles are used to feed power to the grid and this is called as "Vehicle-to-Grid power" (V2G power) [9].

5. Energy Management Strategy (EMS)

The EMS is an overall control system that manages power flows between power sources (PV, SBB, EVB), loads (AC, DC) and utility grid in a flexible and effective manner. It controls the necessary real-time parameters to each of the power converters from the SG system and multiple controllers. The proposed method succeeds in regulating the voltage and balancing the power in the SG system quickly.

In this configuration, the PV array is interfaced with the DC bus by a DC/DC boost converter while both the Stationary Battery Bank (SBB) and Electric Vehicle Battery (EVB) uses bidirectional DC/DC converter to control the charging and discharging processes. The dc and ac networks are interconnected by a centralized inverter. EMS decides the scenarios and selects specific control schemes to be applied to the converters in order to ensure a reliable power environment, depending on the situation of the parameters being monitored. Depending on the PV output power, SOC and power limit of the batteries, DC and AC loads, and the grid demand, EMS decides the operation modes. This results in balanced power flow between the sources and grid to loads [10]. The SOC of the SBB (SOC_{SBB}) and the EVB (SOC_{EVB}) must be between certain limits:

$$10\% \le SOC_{SBB} \le 50\% \tag{12a}$$

$$50\% \leq SOC_{EVB} \leq 95\% \tag{12b}$$

The energy management strategy is applied among the PV system, SBB, EVB, AC load, DC load, Inverter and Grid. This management system controls the energy produced by the PV array and battery storages to supply the demand and operates in following 3 modes:

- Mode 1: $P_{PVMPPT} > (P_{ACLoad} + P_{DCLoad})$ (Batteries Charging). In this mode, PV system generates excess amount of power than the demand. At this time, either EVB or SBB gets charged depending on SOC limits. If SOC of both the batteries is maximum then, the extra power is supplied to the grid through inverter since the inverter operation is bidirectional.
- Mode 2: $P_{PVMPPT} < (P_{ACLoad} + P_{DCLoad})$ (Batteries Discharging). In this mode if PV system provides limited power and had more demand than the generation then, the required amount of power is taken from the batteries and delivered to the loads based on SOC values. If batteries SOC are minimum, the required amount of power is taken from the grid through the inverter.
- Mode 3: In this mode, the SOC of batteries reaches the maximum limits and the maximum power provided by the PV array is higher than the demands and loads. In this scenario, as the batteries are fully charged, and if the grid is unable to absorb the excess power from PV array, the MPPT is switched to off-MPPT to balance the system.

6. Simulation Results

The designed model has been successfully simulated using MATLAB. Various operation scenarios and case studies can be developed by using this model. In this paper, overall output power characteristics are presented. The main objective of providing constant load powers and EV considering as an energy storage in SG environment is achieved. This energy management is done by the different modes of operation that determines the energy balance between the generated energy and the load demand.

After simulation, PV array with an irradiance of 1000W/m^2, and V_{MPPT} of 400V producing a power of 168 kW exchanging among grid, loads, SBB and EVB in different modes is measured. Fig. 7 represents the first mode of operation in which when the PV array is operating in MPPT mode, it is generating power around 168kW which is supplied to the loads based on demand. Once the load demand is supplied, power is used to charge the EVB to the maximum SOC of 95% and 30kW to SBB until the soc limit is reached.

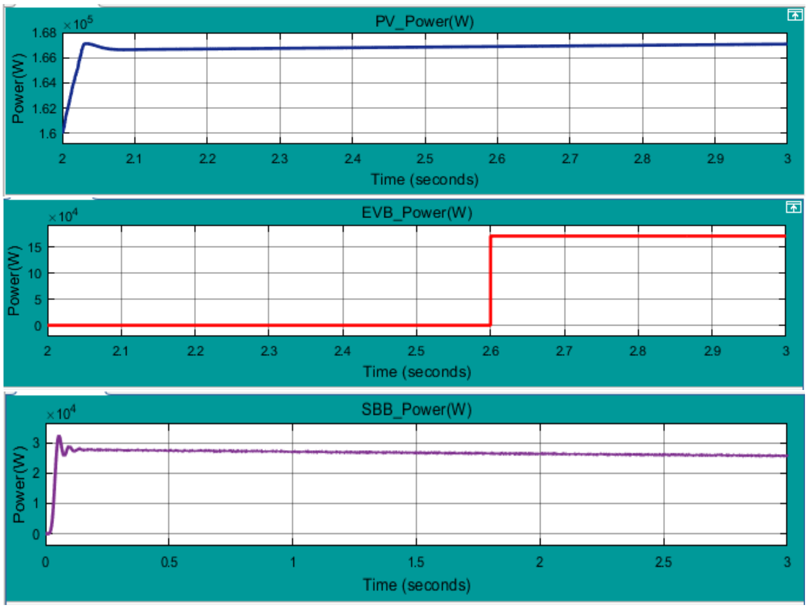

Fig. 7. Mode 1 operation performance

When the load demand is more than 170kW, then excess power of 20kW from EVB and 30kW from SBB is supplied to the load until minimum SOC limits are reached as shown in Fig. 8.

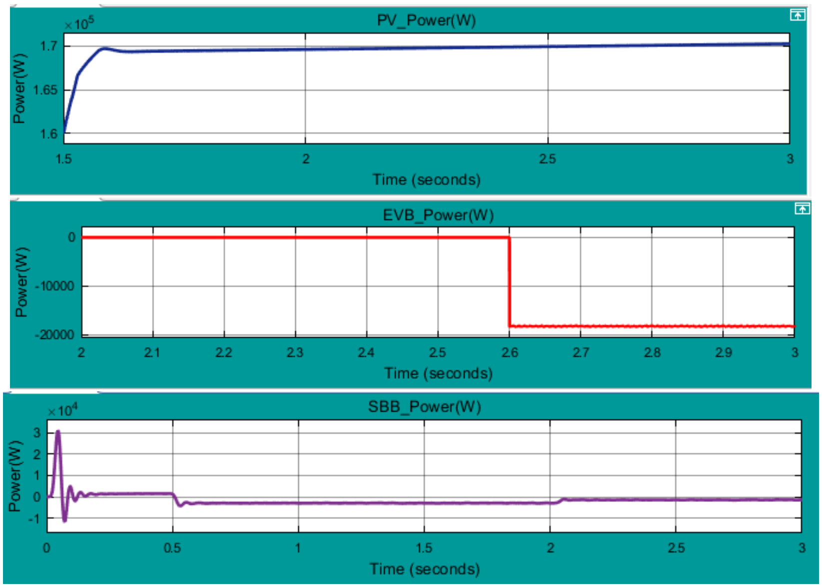

Fig. 8. Mode 2 operation performance

When no power is required for the loads and there is no requirement for grid operation, then the PV array retains to normal mode supplying power of 110 kW from MPPT mode of 168kW provided the SOC limits of both EVB and SBB have reached the upper limits. Since there is no power intake from the PV array, the power values of both the batteries are in idle state that is zero as there is no intake or outgoing from both of batteries as illustrated in Fig. 9.

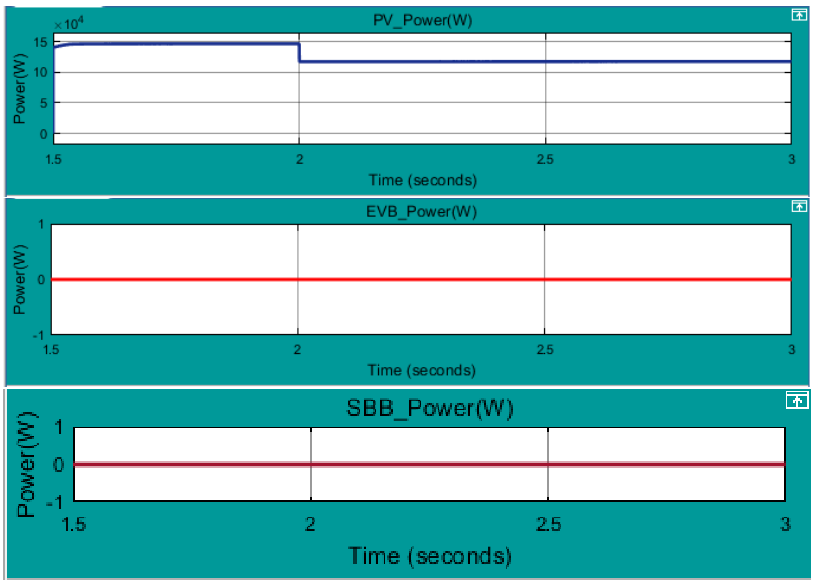

Fig. 9. Mode 3 operation performance

7. Conclusions

The designed Energy Management Strategy (EMS) is applied to a Smart Grid context, where different types of loads and energy utilization patterns interchange energy to reduce the energy dependence from the main utility grid. The results of simulation present the advantage of employing the battery of EV when parked as a System for Energy Storage (ESS). The system's power balance is attained by maintaining a constant DC-link voltage through charging-discharging the batteries with implementation of EMS. This results in enhancement of RESs and using EVs for transport thus reducing the CO2 emissions. Future work will focus on EMS applying to various case studies and working in real time implementation.

Conflict of Interest

The authors declare no conflict of interest with anyone.

Author Contributions

Prof. M. Damodar Reddy designed the research work. Devisree Chippada carried out the research work. Both authors analyzed the data. Devisree Chippada has written the paper. Prof.M.Damodar Reddy edited the paper. Both authors had approved the final version of the paper.

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