A Rule-Based Energy Management System for Smart Micro-Grid

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***Abstract*—With the rapid development of the society, the social energy structure is changing due to the reduction of non-renewable energy including oil, natural gas and so on. Many renewable energy sources (RESs) attract increasing attention in the community. However, most RESs can be easily affected by natural factors, resulting in intermittency and power quality issues in power generation. Consequently, the concept of the smart microgrid (SMG) is proposed. In this paper, a SMG model was established through MATLAB/Simulink integrating a solar photovoltaic (PV) generator and a wind turbine (WT) generator, a battery energy storage system (ESS) through power electronic devices. Then, an energy management system (EMS) was designed to monitor and control the performance of the SMG, and this proposed EMS aimes to maximize generated renewable power and achieve maximum economic benefits. Finally, the cash flow analysis was applied to prove the viability of the entire design.**

Keywords—energy management system, smart microgrid, photovoltaic, wind turbine, energy economy

I. Introduction

Electricity is an indispensable energy source in people's daily life. The fossil fuels have been the world's main sources of electricity. They deteriorate the greenhouse effect and environment pollution. Meanwhile, the deposit of fossil fuels is very limited, and the depletion rate becomes higher and higher, which causes serious energy crisis. Consequently, the research of renewable energy sources (RESs) becomes a hotspot. [1]-[2]

The intermittent nature of RESs including solar and wind power can have adverse effects on the power system, such as low-quality power and inefficiency. The solar photovoltaic (PV) generation system can be easily affected by environment temperate and sunlight intensity. The wind power can be affected by wind speed. These weather and geography factors are altered all the time, which results in unpredictability and intermittency of RESs [3]. On the other hand, the RESs are usually locally accessible and distributed. The traditional power grids are not suitable for RESs integrations since the centralized power generation and long-distance high-voltage transmission of conventional power system has many drawbacks, such as high cost, difficult operation, problems to meet the reliability demand for electricity. Meanwhile, the declining reliability of power system and the declining of power quality are also becoming the burdens of society as the result of the expansion of power grid scale and aging problems of the conventional power grids [4].

To manage the problems and constraints stated, smart micro-grid (SMG) came into being. A typical SMG structure includes RES generation system, such as solar PV generation system and wind turbine (WT), and energy storage system (ESS), energy management system (EMS), metering system, flexible loads and so on. All these components are connected to a common DC bus using power electronic devices. WT, for example, delivers generated power via a rectifier and a boost converter, and similarly PV array is via another boost converter. ESS can help the entire SMG to improve the controllability and maneuverability. It can balance power generation with load requirements. Batteries inside the ESS can achieve this goal through charging and discharging processes controlled by a bidirectional DC/DC converters. Given that household loads are usually AC loads, DC bus connects to these loads and the main grid through a the three-level neutral point clamped (NPC) inverter. The power electronic devices are designed to deliver energy and to provide control signals to make the whole system more stable and reliable [5].

An EMS is a system used to monitor, and control energy generation and consumption. A well-wretched EMS can solve the problems brought by intermittency of renewable generators. It can also accomplish demand side management and enhance economic efficiency [6]. In paper [4], the authors discusses the background, concept, advantages and structure of EMS, and they also cites a number of technologies related to SMGs. In literature [7], a DC EMS are proposed to control PV energy, wind energy and battery, and an optimization strategy for battery system operation and its life expectancy is proposed. In addition, many papers take economic considerations into account when designing EMSs. Paper [8] proposes an EMS based on hierarchical control and analyzes two kinds of market strategies. Literature [9] proposes a distributed power generation side and compares the operation costs of power generation side and demand side and explores the optimization of investment issues.

For this paper, a SMG model was established through MATLAB/Simulink consisting of a solar PV generation system, a WT, a ESS, a EMS and uncontrollable loads. A rule-based EMS was designed to monitor and control the active power flow within the SMG system. The main objectives of this EMS are to: (1) achieve the supply-demand matching, and (2) minimize the costs of electricity generation, energy storage and energy purchasing. By computing values of average daily savings in different seasons, economic viability can be analyzed and proved through calculations of payback period, net present value (NPV) method and internal rate of return (IRR) value. Results show that the proposed SMG can operate properly, and all subsystems can work successfully. The proposed EMS can clearly analyze different power supply conditions and compute the amount of money saved with the SMG connection. In addition, the calculated NPV value is above 0, and the IRR value is above discount rate, which means the economic feasibility is guaranteed.

The structure of this paper is ordered as following. Chapter II introduces the basic compositions of the proposed SMG.

The proposed EMS and its rules are presented in Chapter III, and the demonstration of the whole design with actual data and the economic feasibility analysis are presented in Chapter IV. Finally, the conclusions and the future prospects are presented in Chapter V.

II. PROPOSED SMART MICROGRID ARCHITECTURE

The proposed SMG is modeled in the MATLAB/Simulink software, which consists of three parts. The first part of this model is the RESs generation including a WT and a solar PV generation system which generate power based on specific profiles. These generators connect to a DC bus through specific power electronic devices. The DC voltage from the generators increase to 240 V DC per phase in demand side. The second part is a battery ESS which connects to the same DC bus utilizing a bidirectional DC/DC converter. For the last part, the three-level NPC inverter generates 240 V AC per phase three-phase voltage and feeds the load or transfers power with the main grid. The simulation model of proposed SMG is presented in Fig. 1.

A. PV System

The PV system consists of a PV array and a boost converter, as shown in Fig. 2. The PV array utilized in this part is Kyocera Solar KT200GT with one-module string and one parallel strings. Meanwhile, the maximum power point tracking (MPPT) controller is needed according to the characteristics of PV generation. In this model, the incremental conductance method and the integral regulator is used for MPPT algorithm, which adjusts the PV voltage until the maximum power point (MPP) is reached by comparing the values of the incremental and instantaneous conductance as shown in Fig. 3. The integral regulator is to minimize the error, and its output should be applied to the duty cycle of the boost converter. The MPP is reached when (1) is satisfied, and the error can be presented as (2).

$$\frac{dP}{dV} = \frac{d(V*I)}{dI} = I + V * \frac{dI}{dV} = 0 \quad (1)$$

$$(\frac{dI}{dV} + \frac{I}{V}) \quad (2)$$

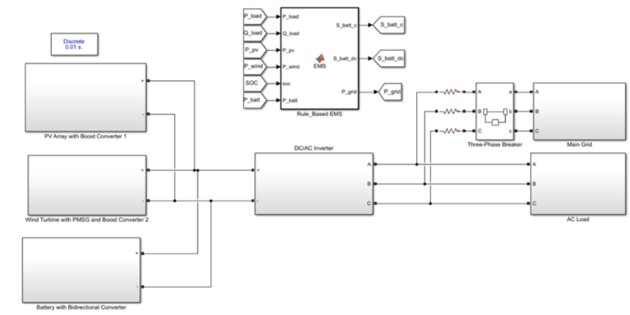

Fig. 1. Proposed smart micro-grid model

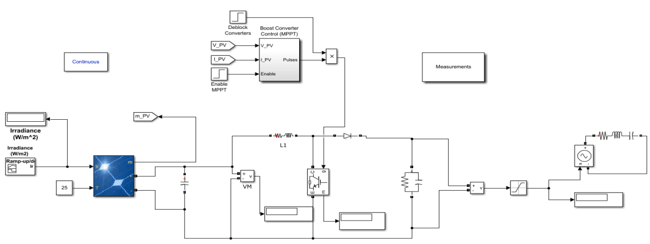

Fig. 1. Photovoltaic model

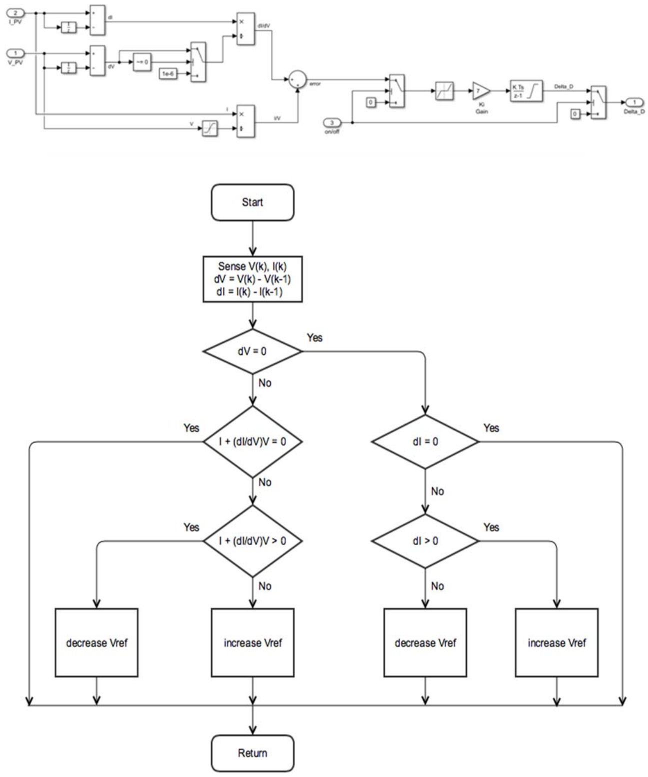

Fig. 2. (a) Maximum power point tracking circuit, and (b) Maximum power point tracking algorithm

B. Wind Generation System

The structure of the proposed WT system is shown in Fig. 4. The model in this part contains a WT, a permanent magnet synchronous generator, a rectifier and a DC/DC boost converter. For a wind generation system, more factors such as pitch angle of the WT and torque control of the PSMG should be considered. To simplify the system constraints, the pitch angle of the WT is set to 0º (mechanical) [10].

C. Battery ESS and bidirectional converter

For battery ESS, the flow of power is in two-way direction, and the charging and discharging processes depend on power flow conditions, as presented in Fig. 5.

The initial state of charge (SOC) is set to 50%, which means the battery's storage capacity accounts for 50% of the maximum storage capacity. When the signal S_batt_c is 1 and the signal S_batt_dc equals to 0, the battery is being charged. When these signals present the opposite values, the current flow in the circuit is opposite to the previous case, indicating that the battery is being discharged.

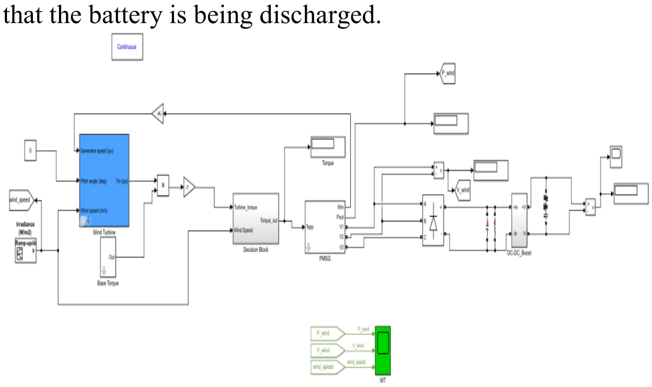

Fig. 4. Wind generation system

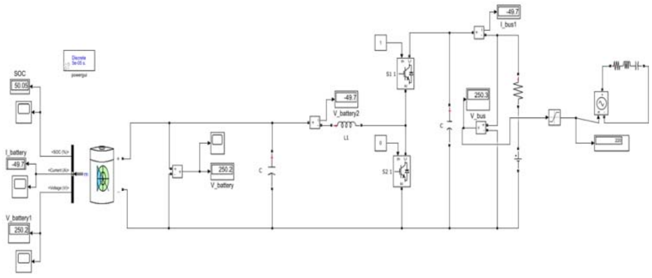

Fig. 5. Battery energy storage system

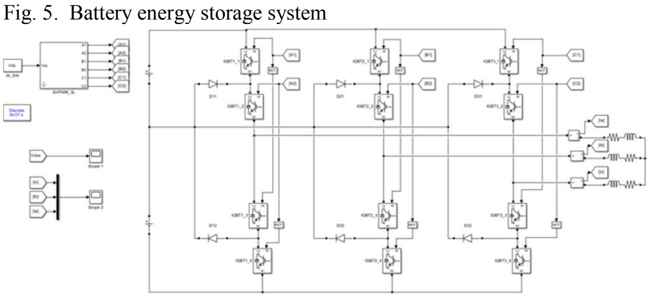

Fig. 6. Three-level neutral point clamped inverter

D. Three-Level NPC Inverter

The three-level NPC inverter utilizes the NPC and series DC capacitors to generate the three levels. Compared with the other types of inverter, this inverter has the benefits of small output voltage and current harmonics and small amount of loss of the switching device [11]. The basic principle of this inverter is 180^{o} (electrical) conduction, which means the conduction angle of each bridge arm is 180^{o} (electrical), and the upper and lower arms of the same bridge are alternately conductive. Meanwhile the angles at which each bridge begins to conduct are 120^{o} (electrical) in turn. At any moment, there will be three bridge arms opening at the same time [12].

For its structure, there are twelve IGBTs used in the topology, as shown in Fig. 6. Each bridge of this inverter requires four IGBTs, four freewheel diodes, and two box diodes. In the entire model, the DC side of this inverter is connected with two capacitors in series in order to provide the neutral point.

III. Rule-Based Energy Management System

A rule-based EMS is established in this section to monitor, control and optimize the power flow and economical outcomes for the SMG.

First, EMS reads data of from the entire system. The inputs of the EMS are as follows:

- Active power requirements (P_load);
- Reactive power requirements (Q_load);
- Generated power by solar PV system (P_pv);
- Generated power by WT (P_wind);
- Battery charging power (P_batt_c); and
- State of charge (SOC).

During the simulation process, reactive power is not considered, so we assume that its value is constant to 0. The generated power from PV system and WT follow the models established in Simulink and given profiles. The initial SOC is set as 50%. Moreover, some internally defined variables including EMS are as follows:

- Retail tariff (RetT);
- Feed-in tariff (FiT);
- Power delivered from battery to main grid (P_b2g);
- Power delivered from battery to the load (P_b2l);
- Power delivered from main grid to the load (P_grid_plus);
- Power provided absorbed the SMG to main grid (P_grid_minus);
- Battery discharging power (P_batt_dc);
- Control signal for main grid (S_grid);
- Control signal for states of the battery (S_batt_c and S_batt_dc); and
- Control signal for renewable generation (S_gen).

A. Objective Function

The proposed EMS is to minimize 24-hour cost of electricity bills, and the objective function is shown in (3). Meanwhile, the cost without installation of SMG with the same load demand can be written as (4), and the average daily saving is also calculated by (5).

$$\min C_{SMG} = \min \sum_{n=1}^{24} (P_{grid_{plus}} * RetT - P_{grid_{minus}} * FiT) \quad (3)$$

$$C_{original} = \sum_{n=1}^{24} P_{load} * RetT \quad (4)$$

$$Saving = C_{original} - C_{SMG} \quad (5)$$

B. Constraints

To find the solution for given profiles, some constraints should be defined first. The main constraints applied for this EMS are mainly from the perspectives of battery and the main grid connection. For the main grid, the power supply and consumption should be balanced, as shown in (6). If the main grid is buying power from the household, the absorbed power is provided by the battery and the renewable generation, as shown in (7). For discharging state, the discharging power flows to the main grid and load, as shown in (8). Similarly, the upper and lower bounds should be considered for the battery and the main grid, as shown in (9)-(13).

P_grid_plus+P_pv+P_wind=P_load+P_batt_c (6)

P_grid_minus=P_b2g+(P_wind+P_pv) *(1–S_gen) (7)

P_batt_dc=P_b2g+P_b2l (8)

P_grid_plus≤ P_grid_M*S_grid (9)

P_grid_minus≤P_grid_M *(1-S_grid) (10)

P_batt_c≤P_batt_M *S_batt_c (11)

P_batt_dc ≤ P_batt_M *S_batt_dc (12)

SOC_m ≤ SOC ≤ SOC_M (13)

where P_grid_M is the upper limit of delivered power with the main grid, which is set to 100kW in simulation; P_batt_M is the ceiling operating power of the battery which is 15kW in simulation; and SOC_m and SOC_M are the lower SOC (40%) and upper SOC (95%) to extend the lifespan of the battery.

C. Various Scenarios

Since the wind speeds and solar insolation depend on different weather conditions, the output of renewable generations is unstable. Consequently, several conditions could occur due to the relationship between the generated power and demanded power, as shown in Table 1.

TABLE I. Various Scenarios

Scenario	Renewable Generated Power	Battery	Main Grid
1	Sufficient	Charging	No connection
2	Sufficient	No action	SMG sells power to the main grid.
3	Insufficient	Discharging	No action
4	Insufficient	No action	SMG buys power from the main grid

D. Summary

Based on the rule-based EMS formulation and several scenarios, EMS rules is established as following:

Rule One:

If $P_{pv} + P_{wind} - P_{load} \geq 0$ and SOC > 95%,

The battery is fully charged, and the demanded power is satisfied by the renewable generations, and excess power is generated and sold to the main grid.

Rule Two:

If $P_{pv} + P_{wind} - P_{load} < 0$ and SOC > 95%,

The battery is discharged, and the demanded power is provided by the renewable generations and ESS.

Rule Three:

If $P_{pv} + P_{wind} - P_{load} \geq 0$ and 40% < SOC < 95%,

The ESS operates in a charging battery mode until the fully charged battery or increasing demand of the load.

Rule Four:

If $P_{pv} + P_{wind} - P_{load} < 0$ and 40% < SOC < 95%,

The ESS operates in a discharging battery mode, the ESS is utilized to compensate the power demand.

Rule Five:

If $P_{pv} + P_{wind} - P_{load} \geq 0$ and SOC < 40%,

The battery is discharged by the excess power generated by the renewable generations.

Rules Six:

If $P_{pv} + P_{wind} - P_{load} < 0$ and SOC < 40%,

The SMG buys energy from the main grid until the generated renewable power or the SOC increase. The rule-based EMS is coded in MATLAB/Simulink as show in Fig. 7.

IV. Simulation Results and Analysis

The typical days in four seasons are simulated based on different sets of data. These data are recorded evert half an hour including load demand, solar insolation, temperature and wind speed. The simulations results are presented as the following.

A. Simulation Settings

Case one simulates a typical day in summer in Australia which is from Nov. 1st Jan. 31st. Since the load requirements vary greatly from one day to another, a typical day in summer is chosen by averaging the energy demand at each point of all summer days. Then, the load profile for the typical day in summer is obtained, as shown in Fig. 8. Similarly, the load profiles for typical days in autumn, winter and spring can be obtained which represent case two, case three and case four respectively. Moreover, the input data for PV and wind generation systems are shown in Fig. 9-11.

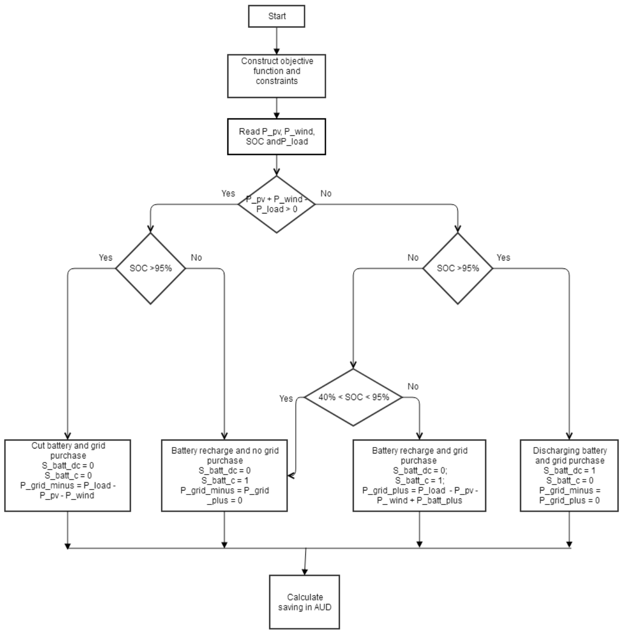

Fig. 7. Energy management rules

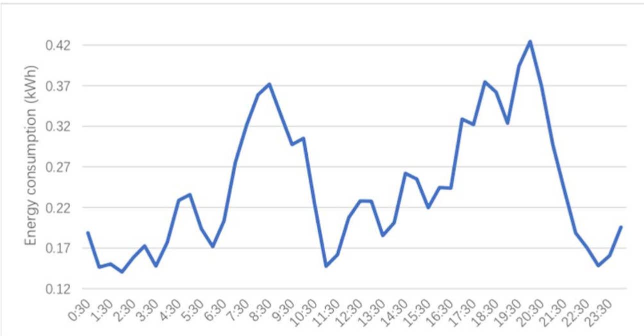

Fig. 8. Load profile for typical summer day

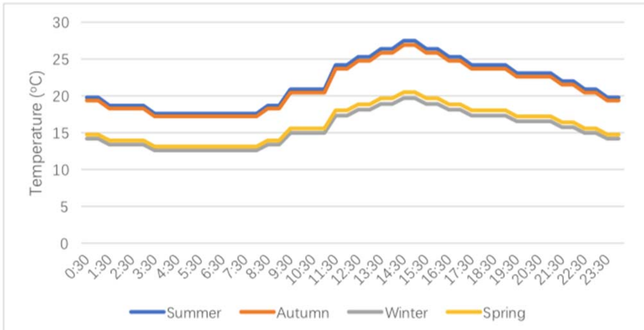

Fig. 9. Temperature data for photovoltaic generation system

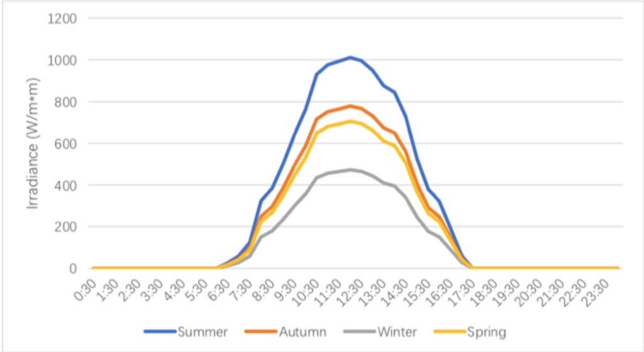

Fig. 10. Irradiance data for photovoltaic generation system

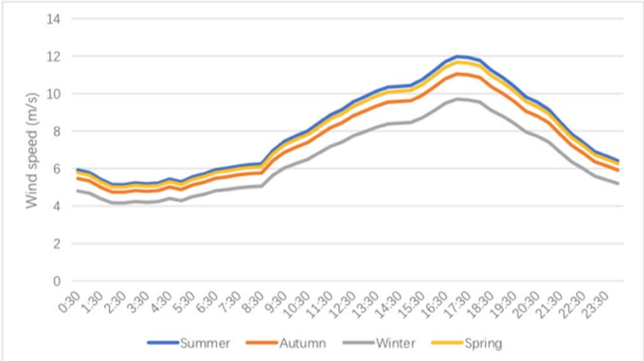

Fig. 11. Wind speed data for wind generation system

B. Simulation Results

The total saving in case one is calculated and equals to AUD1.58. This value can be treated as average saving per day in summer. Since the summer contains 92 days, total saving in summer is AUD145.69. The simulation result is shown in Fig. 12. Different shaded parts represent different meanings, as followed:

- Active power requirements (P_load);
- Reactive power requirements (Q_load);
- The shaded blue part represents the power delivered from the main grid to the load;
- The shaded orange part is the power absorbed by the load from the battery;
- The shaded yellow part is the power provided by photovoltaic (PV) and wind turbine (WT) to load;
- The blue curve outlines the electricity power generated by renewable generations which is the sum of the PV and WT power.
- The black curve represents the total load demand; and
- The shaded purple refers the excess renewable power delivered to the battery.

From this result, several scenarios can be observed for several specific intervals. Point A indicates the scenario 3, which is around 5 o'clock, and the PV array and WT cannot provide enough power to demand side and the required power is absorbed from the main grid. Point B, which is between 0 o'clock and 6 o'clock, indicates scenario 4. The power generated from the renewable generation is insufficient, and the extra power is obtained by discharging the battery. Point C, which is around 12 o'clock, indicates scenario 1. The

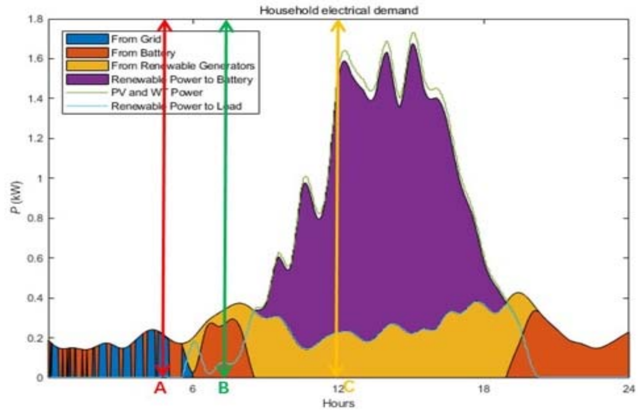

Fig. 12. Simulation results for case one

Table II. Total savings in several cases

Average Seasonal Cost Savings (AUD/day)			
Summer	***Autumn***	***Winter***	***Spring***
1.59	1.19	1.29	0.83
Total Seasonal Cost Saving (AUD/day)			
Summer	***Autumn***	***Winter***	***Spring***
145.70	105.79	119.63	73.89
Total Annual Cost Saving (AUD)			
445.00			

RESs provide a large amount of power, and the generated power is more than the demanded power at that moment. The electricity generated not only provides power for the load, but also charges the battery. Similarly, the total savings in all cases are calculated, as shown in Table 2.

C. Economic Feasibility Analysis

The fixed cost refers to the cost do not change within certain range of time and workload. Here, the capacity of installed SMG is set to 5kW, and the average cost is set to AUD2 million/MW [13]. As a result, the initial cost of the proposed SMG is around AUD4000. The economic feasibility is analyzed through calculations of payback period, NPV method (14) and IRR value.

$$NPV = \Delta A * PVF(d, n) - \Delta C \quad (14)$$

where ΔA is the cost savings per year after the SMG is applied, PVF(d, n) equals to $\frac{(1+d)^n - 1}{d(1+d)^n}$, d is the discount rate, n the cycle of this system, and ΔC the initial investment. This system is assumed to last for 15 years, since during this time, the cost of updating equipment may not be considered. The electricity escalation price is 2.6% per year [14]. The discount rate is 6.75%, and the annual inflation rate is 2.1%. [15] As a result, the actual discount rate is:

$$d_{actual} = \frac{1+d}{1+e} - 1 = \frac{1+0.0675}{1+0.021} - 1 = 4.6\% \quad (15)$$

Under this condition, the cumulative cash flow calculation is shown in Fig. 13. When the year 15 ends, the NPV value is calculated in (16). Since this value is above 0, the system is feasible within 15 years and the investment is worthy. Moreover, the rate of return that yields NPV=0 should be calculated during the decision making, as shown in (17)-(18).

$$NPV = -4000 + 455 * \frac{(1+4.6\%)^{15} - 1}{4.6\% * (1+4.6\%)^{15}} = 746.41 \quad (16)$$

$$NPV = -4000 + 455 * \frac{(1+IRR)^{15} - 1}{IRR * (1+IRR)^{15}} = 0 \quad (17)$$

$$IRR = 7.21\% \quad (18)$$

Since the value of IRR is more than the discount rate, this system can be invested by users.

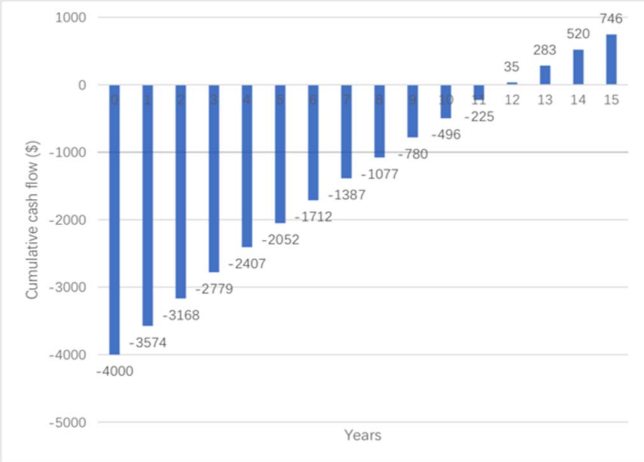

Fig. 13. Cumulative cash flow

V. CONCLUSION AND FUTURE WORKS

A SMD model based on Simulink/MATLAB with a rule-based EMS is proposed in this thesis. Through collection and analysis of real-life data, the representative profiles including four typical days over a year are utilized as the inputs of the SMG. The EMS is used to help users to reduce their electricity costs while ensuring adequate demanded power. Several scenarios are defined according to different situations of power supply and consumption. In addition, the original cost without installation of SMG, the cost with SMG and the average daily saving can be calculated with specific retail tariff and feed-in tariff values. The results confirm that this proposed SMG and EMS can save users large amount of costs in four seasons. Finally, to analyze the economic feasibility of this project, NPV method, payback period and IRR method are utilized. From calculation results in this part, this SMG is worthy of investment.

The EMS proposed in this paper is optimized for only one goal which is cost minimization. In my future work, multifunctional EMS can be designed. Moreover, this article focuses on the active power and ignores the reactive power. To achieve high power quality, voltage control and frequency control, the four-quadrant control should be considered. Last but not least, the discussed EMSs is offline EMS with steady-state control algorithms. Given inputs data makes the optimization easier. However, in reality, these EMS algorithms might not be feasible since the input data is unknown and predicted control is required. Consequently, in future works, dynamic algorithm should be developed and applied to the SMG, for example, the modern predictive control (MPC) can be utilized to realized online simulation of the SMG.

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