

Control Strategy for a Micro Smart Grid to Meet the Energy Demand of a Household

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Abstract. Tri-generation systems are regarded as one of the most efficient technologies to save energy consumption and reduce carbon emission. In this research, a smart grid using renewable energy and energy storage unit is studied as the electrical part of a tri-generation system. This study aims at satisfying the dynamic demand of a household and discusses the control strategy. The controlling method is divided into two situations, namely with renewable energy source and without renewable energy source, and both the processes are presented in detail. The controlling strategy is proven to be useful for the operation of this smart grid system.

Introduction

A tri-generation system refers to a system that offers three kinds of energy products. A wide range of products could be generated by a tri-generation system such as heating, cooling and electricity. In this research, the tri-generation system produces electricity, heating and cooling for the domestic household in the UK. The tri-generation system has drawn a broad interest for its high economic benefits in the energy supply process. As the updating of the large volume of the grid system is widely applied, a drawback of the grid electricity supply could be the resistance to unexpected destructive events. The power grid has the features of stability, synchronization and interconnection. However, because of these features, expected step-out events such as typhoon, frost damage and warfare may result in the overall breakdown of the power grid. Additionally, for remote areas, the access of energy supply from the grid is not stable and the quality of service costs a large amount. The construction period is long and potentially unstable. This situation addresses the demand of the research on the tri-generation system. The controlling strategy design of this system is presented in this article.

Recently, research on the CCHP system has drawn attention worldwide. Promotions on the deployment of the CCHP system for residential, commercial and industrial sectors have been introduced in many regions [1]. Simulations and experimental tests have been done during the research on the CCHP system based on the related reviews. Wang presented the experimental and simulation investigation of a micro-CCHP. This research focused on the thermal management controller. The structure was introduced and this system was designed to obtain a higher performance. The results indicated the energy capacity of this system [2]. Another similar research was conducted by Wang on the simulation and evaluation of a CCHP system with exhaust gas deep recovery and thermoelectric generator. The primary energy saving and the cost were evaluated as a proof of the system's innovation [3]. The operation of a design was also focused. In one research, the system was driven by the internal combustion engine. The efficiency of the operation mode was analyzed. The research was made on the operation of absorption heat pump and condensation heat recovery [4]. The system supported the fuel cell for residential applications. The efficiency of components was compared as an evaluation for tri-generation [3].

Tri-generation systems are widely connected with the application of renewable energy. A dynamic optimization-based tri-generation system was combined with renewable energy and storage system for the energy supply of electrical vehicles. The optimization of the system aimed at

reducing the operation cost and carbon emissions. The optimal operation was conducted by a central controller, which was proven to improve the energy using the efficiency of the Savona Campus [5]. The prediction was also applied in the research of tri-generations. One research used the reduction and analysis to improve the performance of the tri-generation system and reduce the carbon emissions [6].

Many articles have researched the performance of tri-generation for several appliances. However, these articles lacked an effective controlling method for the domestic load. No research combined the simulation of the system with the experimental tests on the domestic load's supply. Renewable energy was mentioned in the former research, and it should be applied as the energy sources for the tri-generation system. This article introduces the research process of a novel smart grid system. The controlling system is designed based on the SIEMENS S7-200 PLC model. Simulation software has the function of measuring the performance of the system. The energy source of this system includes the generator sets, a wind turbine and solar panels combined as the energy source of this system. This system contains the function of DC energy transfer and AC energy supply that was different from a normal micro-scale energy generation. With a parallel energy source, the system has a serial of functions such as electricity generation, energy storage, transmission, control and protection, which guarantee the stability of this system. The inverters and converters are all connected with the data collector. With the connection of RS-485, the control center could ensure the capacity of resisting disturbance. The results of the simulation and experimental tests indicate the higher efficiency performance and the stability of this system.

System Structure

This system consists of four parts: energy generation system, energy storage system, controlling system and distribution system.

(1) In the designed experimental test, the energy generation system is a combination of diesel engine and the renewable energy source. The diesel engine used bio-oil as the fuel. The renewable energy system includes the solar power and the wind turbine. The operation of energy sources will depend on the energy demand.

(2) For the energy storage unit, the batteries could supply the energy rate of 2 KW in 20 minutes for a long time. The super-capacitors could supply a higher rate (3 KW) in one minute for a period of 20 minutes.

(3) The control system is the main aim in this article. For supplying energy to the specific load of a household, the operation strategy and the protection of the system are presented.

Analysis of the Power Rate. Based on the system's structure, the energy source will merge in the DC mother line. After the filter and the inverter, the energy will be supplied to the load by the mother line.

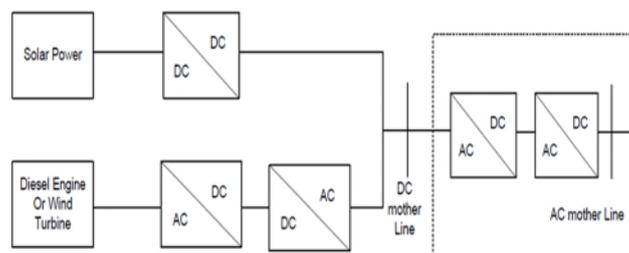


Fig. 1 System structure of the grid bench.

The components in the dotted line indicate transferring DC energy to AC energy. The inverter connects the DC energy and the AC energy. The equivalent circuit is shown in Fig. 2.

In this figure, $U_o \angle \theta$ is the idealized AC energy source; I is the load current; Z is the impedance in the transmission line; and $U_o \angle \theta$ is the AC voltage of the right side. The PWM inverter could change the range and phase of the AC energy. The reset rate is also available for adjustment.

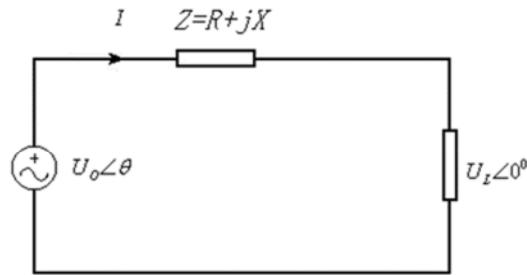


Fig. 2 The equivalent circuit of the energy source.

Compared with the traditional transmission line, the energy transmission for the smart grid shows a different characteristic. The traditional grid constitutes a high-voltage transmission system. The transmission grid is inductive; normally, it needs to connect with a capacitor in parallel for a compensation with a certain amount of reactive power. The transmission grid of the micro smart grid shows resistance. In the high voltage transmission, the impedance is larger than resistance. In the transmission of the micro grid, the resistance is larger than impedance.

Information about the comparison is given in Table 1.

Table 1. Information about the transmission line.

Cross-sectional area (mm^2)	10	16	25	35
Impedance (Ω/km)	3.08	1.91	1.20	0.868
Resistance (Ω/km)	0.36	0.34	0.33	0.30

Analysis of High-Voltage Transmission. Because the impedance is much larger than the resistance as revealed in the dynamic analysis, the resistance should be neglected ($R=0$). On the basis of the equivalent circuit, the power and current are expressed by the following equations:

$$S_L = P_L + jQ_L = IU_L \tag{1}$$

$$I = \frac{U_o(\cos\theta + j\sin\theta) - U_L}{jX} \tag{2}$$

Based on the above equations, the active and reactive power can be expressed as follows:

$$P_L = \frac{U_o U_L \sin\theta}{X} \tag{3}$$

$$Q_L = \frac{U_L^2 - U_o U_L \cos\theta}{X} \tag{4}$$

Analysis of Micro Grid Transmission. Based on the equivalent circuit, the active power and reactive power can be expressed by the following equations:

$$P_L = \frac{U_L}{R^2 + X^2} [R(U_o \cos\theta - U_L) + XU_o \sin\theta] \tag{5}$$

$$Q_L = \frac{U_L}{R^2 + X^2} [RU_o \sin\theta - X(U_o \cos\theta - U_L)] \tag{6}$$

Because the impedance in the circuit is small, which could be neglected, $X=0$ in the circuit, and thus the active and reactive power can be expressed as follows:

$$P_L = \frac{U_L}{R} (U_o - U_L) \tag{7}$$

$$Q_L = \frac{U_L}{R} U_o \sin\theta \tag{8}$$

Based on the above equations, the power transmission in the normal and smart grids is different. The change in the node voltage will have an influence on the reactive power.

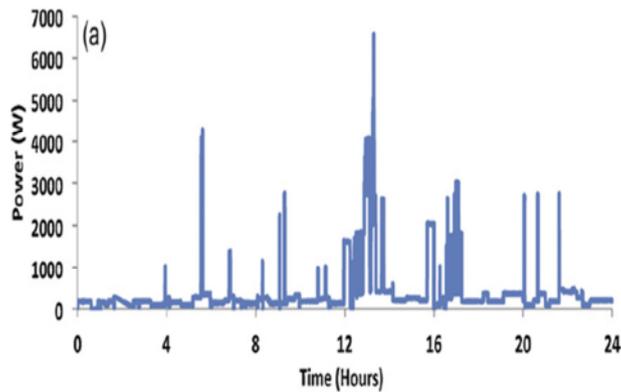


Fig. 3 Electric energy demand for a typical household.

Domestic energy demand study is the basic part of the research. Thus, the aim of the project is to investigate how the tri-generation system can meet the demand of the domestic energy consumption. This is necessary for the system’s design. First, the specific controlling system meets the electrical demand. Based on the power consumption, the controlling system must have the ability to meet the demand with high efficiency. All the operation strategy and the size of the system are based on the investigation of domestic energy consumption.

Working Strategy Designing

Hardware Structure. As shown in Fig. 4, the calculation of the controlling is done by using the model Siemens S7-200 PLC. The voltage and current signals are transported to the analog quantity, expanding unit-EM235 as a format of 4-20 mA current signal. After the processing of the signal, the PLC will send a command to control the system.

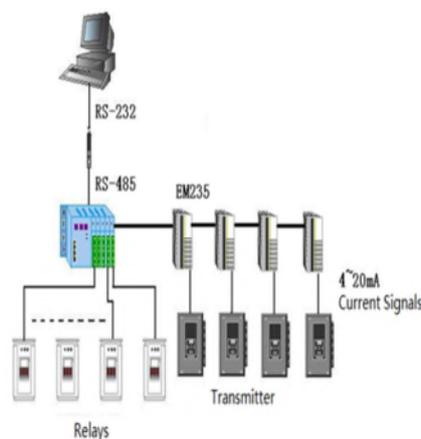


Fig. 4Controlling system combined with the signal displaying system.

Features of the Structure of the Controlling System. 1. S7-200 PLC as an individual controlling center unit, the logic calculation, the analysis of the measuring signal and the command sending process are all processed in this unit.

2. PC is operated as the inspection unit. The controlling command could be generated by the PC and the working state of the grid is displayed on the PC. The calculation is not implemented in this part.

3. The connection between the PC and PLC is a signal cable with the connectors RS-232 and RS-485.

4. The voltage and current signal measured on the system are transferred to analog signals and then transported to EM 235.

5. The controlling system can operate individually, independent of the PC. The PLC is used for controlling all the equipment.

System's Controlling Strategy. In the operation of the same grid, the key point of the strategy is to balance energy resources and the energy demand. Once the unnecessary energy consumption is avoided, the maximum economic efficiency can be obtained. This research aims at designing and implementing adequate controlling by the approach of adjusting the working sequence of the switches in the system.

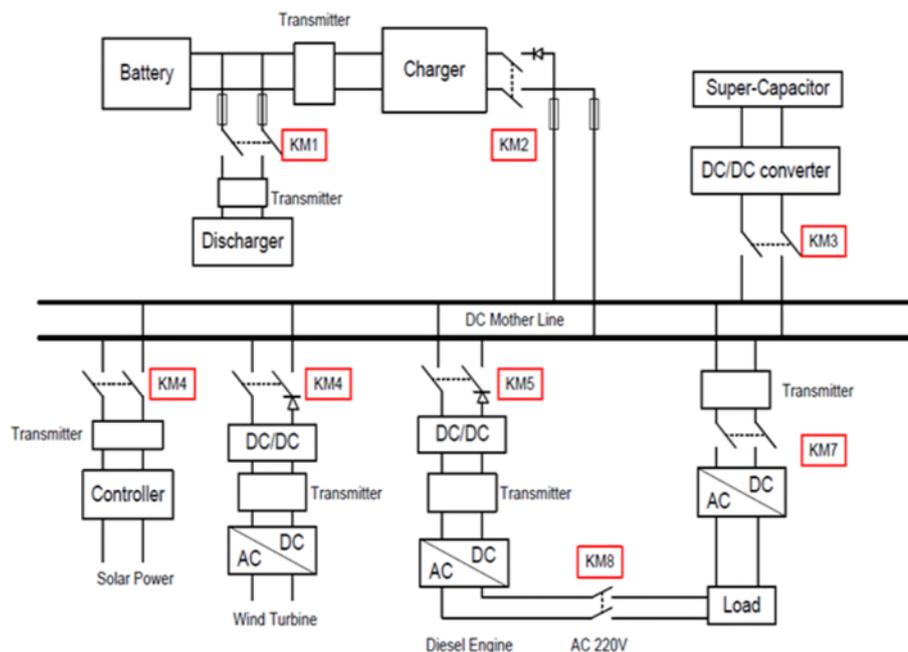


Fig. 5 System configuration.

All the electrical equipment in the smart grid system can be controlled by the controlling switch from KM1 to KM 8. KM 8 prepares to stop the diesel engine's operation when a fault in fact occurs. The normal state of the switch KM 8 is off. The energy source in this project includes diesel engine, solar power and wind turbine. In this operation session, renewable energy is not applied. Different situations refer to various operation modes, and the details are presented. The first scenario is the operation strategy of this system without the renewable energy sources.

Control Strategy for the System without Renewable Energy Source. 1) When the load is less than 1 KW: When the power offered by the batteries and the super-capacitors could meet the energy demand, KM6, KM2 and KM8 are off while KM1, KM3, and KM7 are open. In this state, the energy demand is supplied only by the batteries and the super-capacitors. When the energy storage could not meet the energy demand, the diesel engine needs to operate to supply extra energy for the load. In this state, KM1 and KM8 are open while KM2, KM3, KM6, and KM7 are off. When the batteries and super-capacitors are fully charged, the system will turn to the former operation state.

2) When the load is larger than 1 KW and less than 6.5 KW, the diesel energy will operate for supplying energy. At the same time, the energy storage will be charged. In this state, KM1 and KM8 are open while KM2, KM3, KM6 and KM7 are off. The controlling system will stop charging when the energy storage system finished one hour of floating charging. The operating

process for this logic option is that KM1, KM2 and KM8 are open while KM3, KM6 and KM7 are off.

3) When the load is larger than 6.5 KW and less than 10 KW, the diesel engine will work with the storage unit together for supplying energy. The maximum energy rate can exceed 10 KW. In this state, KM2 and KM8 are open while KM1, KM6 and KM7 are off. When the capacity of the energy storage unit is low, alarm will respond and gives a warning. KM1 will be set as off to protect the energy storage unit for over discharge. If the energy storage unit is in a state of severe over-discharge, then KM6 will be open with an alarm.

Control Strategy with Renewable Energy. When the system has multi-energy source that includes wind turbine, solar energy and diesel generator, the operation strategy will have some adjustments because of the instability of the renewable energy sources.

1) When the load is lower than 1KW: The energy sources will be a wind turbine, solar power, and electrical energy storage unit. If the solar power and the wind turbine could meet the energy demand of the load, then the energy storage will be in a state of charging. The logic state of the switches is as follow: KM1, KM6 and KM8 are open; KM2, KM3, KM4, KM5 and KM7 are off. When the power rate could not satisfy the load, the energy storage units will begin to supply energy for the load. The logic state of the switches is that KM2, KM6 and KM8 are open while KM1 and KM3, KM4, KM5 and KM7 are off. When the total energy rate of the renewable energy and the energy storage set could not satisfied the energy demand, the diesel engine will begin to operate for supplying and charging the energy storage unit. The logic state of the switches is that KM1 and KM8 are open while KM6, KM2, KM3, KM4, KM5 and KM7 are off. The engine will stop when the energy storage unit enters float charging. In this state, engine will stop and the renewable energy source will be mainly responsible for supplying energy.

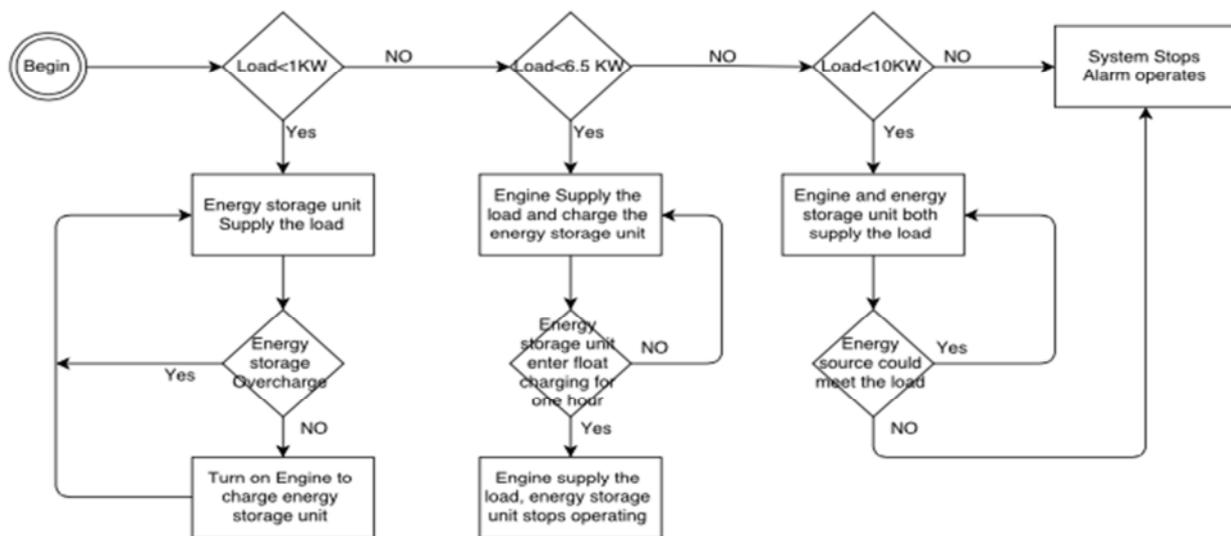


Fig. 6 Operation logic map for the system.

2) When the load is larger than 1 KW and less than 6.5 KW: The diesel engine will begin to supply energy with the renewable energy source. The energy storage unit is in a state of charging. The logic state is that KM1, KM6 and KM8 are open while KM2, KM3, KM4 and KM7 are off. The energy storage unit is a set of floating charging, and the charging circuit will stop one hour after float charging. Then, the logic state is that KM1, KM and K<8 are off while KM4, KM5, KM6 and KM7 are open.

3) When the load is larger than 6.5 KW and less than 10 KW: All of the energy source will supply the load. The maximum power rate can exceed 10 KW. The logic state is that KM2 and KM8 are open while KM1, KM3, KM4, KM6, KM6 and KM7 are open. When the capacity of energy storage units is not sufficient for supplying energy, KM6 will operate to alarm and stop the discharging.

Conclusions

The purpose of this research is to design a control strategy to solve the controlling problem of the energy supplying process. In the whole controlling period, the controlling strategy implements automatically. At the same time, the data collection unit will make sure that the energy demand is satisfied with the same grid. It is an environmental-friendly system. The carbon emissions are much lower than the similar system. The system strategy is proved to be reliable and stable. The overload, short circuit and circuit break are all considered in the controlling strategy. By applying this controlling strategy, the system can exceed high economic efficiency. Based on the scientific calculation, this strategy is an advanced operation strategy for this same grid system.

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