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OPTIMAL ENERGY MANAGEMENT OF PV-GRID CONNECTED HOUSEHOLD NANO GRID SYSTEM USING FUZZY LOGIC CONTROL

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ABSTRACT: Grid-connected household nano-grids are playing a key role in meeting the rapidly increasing energy demand. The adoption of residential photovoltaic (PV) power generators combined with energy storage system can reduce the energy dependency of individual households while alleviating the impact of intermittent solar energy on the electric power grid. A long-term optimal scheduling algorithm is proposed to better organize the battery charging/discharging action in PV grid connected household nano-grids. The algorithm is based on the rolling optimization method and the optimization problem is solved by the mixed integer linear programming. Moreover, a smoothing function is introduced to alleviate the power fluctuation of the exchanging power between the nano-grid and the main grid, caused by the intermittent PV generation and the stochastic residential loads. A battery and a super capacitor, composing a hybrid energy storage system (HESS), are controlled to absorb the low and the high frequency components of HESS power respectively. This paper builds on the optimal energy management of PV-grid connected household nano grid system using fuzzy logic control (FLC). The resulting system can be implemented to control power flows in other systems composed of photovoltaic generation and energy storage. The results confirm the operational and economic benefits of using the optimal operational strategy, through the fuzzy rule base.

KEYWORDS: nano-grid, hybrid energy storage system (HESS), photovoltaic (PV), smoothing function, fuzzy logic control (FLC).

I. INTRODUCTION

The technical environment of the current power system has changed drastically due to the integration of Renewable Energy Sources (RES) [1]. Massive interfacing of these variable power sources leads to the evolution of smart grid [2]. However, the fact is that the operators still have to face the great challenge of integrating this kind of sources into the power system. Many solutions were proposed to dilute or to address these technical issues.

The significant or main RES include mainly solar PV [3] and Wind energy systems [4]. The major advantages of these are, they contribute pollution-free energy and causes no greenhouse gas to be emitted, virtually no maintenance is required as solar panels last over 30 years in the case of solar PV, can be installed virtually anywhere, can integrate batteries for reliable operation. The Maximum Power Point Tracking (MPPT) [5] method accurately tracks the maximum available power from a solar PV.

Load flow analysis is one of the fundamental analysis in power system [6]. Load flow analysis is a steady state solution technique which is obtained by considering power flow during a very short interval of time, during which power flow through transmission line remains constant. In load flow analysis we calculate total power flowing away from a bus and voltage phasor at that bus. Hence we calculate injected real power (P), injected reactive power (Q), voltage phasor magnitude (|V|) and voltage phasor angle (δ) at all buses maintaining power balance equation and variable limit constraints. As power system network is becoming more complex day by day due to addition new network components, so we need a method which will converge the solution as quickly as possible. Renewable energy integration can be further improved through the deployment of hybrid energy sources [7] and the use of energy storage (ES) systems. These technologies also increase grid reliability and economy, compared to singlesource generation without storage. An important example of hybrid technologies with rapid uptake in the residential market are photovoltaic (PV) generation systems combined with home energy storage systems (HESS) [8]. Such PV /HESS installed locally at individual households can provide significant cost savings by reducing the need to purchase energy from the grid. In addition, such systems contribute to better balancing of the entire power grid by smoothing out peaks in power demand and production. They produce extra power when the solar radiation is higher than local demand, and store the energy for later usage when the solar radiation weakens or the demand increases.

II. RELATED WORK

Integration of intermittent, renewable energy sources into existing electric power grids is a difficult task. The most important approaches include demand control and energy storage. Demand control requires shifting significant energy loads in time to coincide with periods of large energy production. Energy storage systems maximize local self-consumption of energy and smooth out the amount of energy supplied to and drawn from the grid.

Combination of Active Demand-Side Management (ADSM) and ES systems has been studied by Castillo-Cagigal et al. [9]. They analyzed the effect of such hybrid approach on the local energy consumption and proposed a prototype of a selfsufficient, grid-connected house equipped with PV generation, batteries, controllable appliances, and smart metering. Taking advantage of historical data on energy production and consumption, Martins et al. determined optimal power flows in a residential PV IHESS to minimize the overall energy costs. Using linear programming, the authors obtained optimal distribution of PV energy production and optimal composition of sources to satisfy energy demand. Considering data for an entire period of one year, the resulting time series represent ideal distribution of power flows taking into account not only solar energy harvestable at the current time, but also energy available in the future time steps. However, this approach cannot be used to manage energy in real time, as the future energy availability is not available with sufficient confidence.

Fuzzy logic:

Fuzzy logic is a logic which deals with imprecise value that lies between [0,1]. The real number which is truer is nearer to 1 and nearer to 0 if it is less true [10]. The trueness is called degree of membership of that quantity. The expression about any quantity in our day to day life is not precise. We generally like to express the quality of a data in terms of some linguistic variable like, more, less, good, bed, high, low etc. based on our own experience and belief. Fuzzy logic is the logic as per our communication language about certain quantity, which is not precise. Lotfi A. Zedeh , in 1965 for the first time worked on fuzzy logic.

Power fluctuation of the PV nano-grid is caused by the uncertainty of PV power generation and power demand of residential loads. HESS deploys constant power control as a way to alleviate the power fluctuation of

PV nano-grid. However, the rapid changing charging/discharging current has an impact on the lifespan of battery. The battery will be damaged due to rapid and frequent charging/discharging during power fluctuation. In order to prevent the damage of battery, a super capacitor is used to realize the rapid and frequent charging/discharging, which can effectively alleviate high frequency component of power fluctuation in the PV nano-grid. The hybrid use of battery and super capacitor can be complementary. With reasonable coordination between battery and super capacitor, this HESS can alleviate power fluctuation of the PV nano-grid with the deployment of constant power control.

III. FUZZY LOGIC CONTROL BASED OPTIMAL ENERGY MANAGEMENT STRATEGY

A long-term optimal scheduling algorithm is proposed for the HESS of the PV nano-grid, to better organize the charging/discharging action of the battery. The rolling optimization technique is used to generate hourly optimal scheduling decision. Moreover, a smoothing function is designed to alleviate the power fluctuation of the main grid in minute's level caused by real-time PV and load variations. Fig. 1 shows the schematic diagram of the optimal energy management strategy of PV-grid connected household system using fuzzy logic control.

3.1 Long-Term Optimal Scheduling:

Based on the prediction data of PV power generation and load prediction data in 24 hours, the time of use (TOU) electricity price and battery SOC, the long-term optimal scheduling algorithm can determine the charging/discharging action for the battery in HESS. A rolling optimization is designed to solve the long-term optimal scheduling problem for HESS. In this rolling optimization, 24 hours are seen as a cycle and one hour is defined as a scheduling time span to realize optimal power scheduling. At each power scheduling point, which has one hour interval, the optimal power values are scheduled for 24 hours. However, only the first optimized vector is used as other 23 optimized vectors are not accurate and abandoned. The adopted optimized vector shows the current operation state of the PV nano-grid.

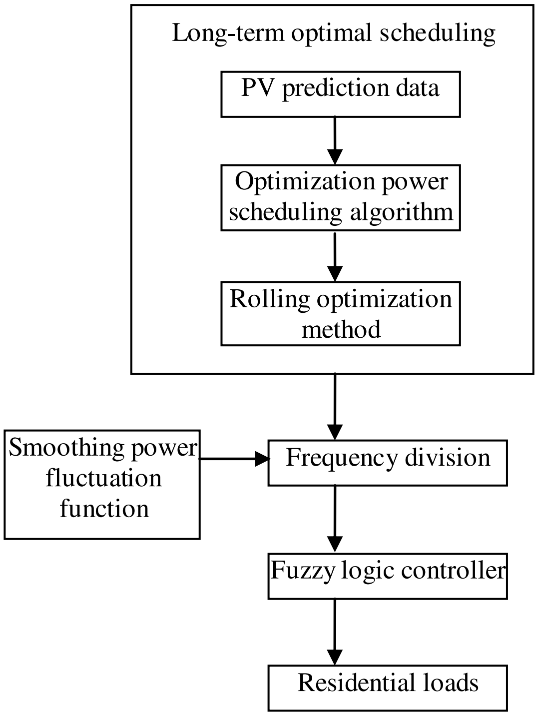


Fig. 1: OPTIMAL ENERGY MANAGEMENT STRATEGY

Therefore, with the power scheduling points going on, the data in optimization data window is updated when rolling every one hour. The prediction error can be reduced since the length of optimization is considered in the rolling optimization. Optimal schedule power command reserved at every one hour power scheduling time points can be achieved by using rolling optimization method.

3.2 Smoothing power fluctuation function:

The long-term optimal scheduling for ESS is based on the prediction of PV power, loads and ToU price. Due to the intermittency of PV generation and residential loads, the power fluctuation of PV and residential loads in minute level is hard to predict. When the power fluctuation range of PV and residential loads in minute level is within 5% of the exchanging power, the main power grid can adjust it by itself. The operation of main power grid will not be influenced. However, when the power fluctuation range of PV and residential loads in minute level is above 5% if the exchanging power, it can cause the fluctuation of voltage and frequency in the main grid, which adversely influences the operation of the main grid. Therefore, a smoothing function is added in this energy management strategy to smooth the power fluctuation of PV and residential loads in minute level.

3.3 Household Load Prediction:

Residential loads are inherently random. In the long-term optimal scheduling algorithm, the load prediction is based on the history data of the residential load usage. The load prediction used in this paper is based on the double exponential smoothing method for 24 hours prediction. In the double exponential smoothing method, the predicted value has a high fitting degree with its original time sequence.

3.4 Optimal Power Flows:

The optimal solution must satisfy all constraints described above. It aims to reduce the overall cost by minimizing the expenses for energy purchase and implicit cost caused by the battery degradation. This cost model is divided into three components, i.e.minimize

$$\boldsymbol{C_{tot}} = \boldsymbol{C_{buy\_E}} + \boldsymbol{R_{sell-E}}$$

The first component $\boldsymbol{C_{buy\_E}}$ comprises the cost of energy purchased from the grid, while the second component $\boldsymbol{R_{sell-E}}$is the revenue from PV energy generation exported to the grid. These two components are evaluated as follows,

$$\boldsymbol{C_{buy\_E}} = \sum C_{buy} . P_{grid-load}$$

$$\boldsymbol{R_{sell-E}} = \sum C_{cell} . (P_{PV-grid} + P_{batt-grid})$$

3.5 Fuzzy logic control (FLC):

The current fuzzy logic controller uses two input variables, one output variable, and a rule base of 15 fuzzy rules. The input variables, used by the controller to devise efficient PV/HESS system operations, reflect the state of the system and environmental conditions at the time of control intervention, i. The first input variable, residual load, is defined as the difference between electrical demand and locally generated PV power,

$$rLoad_i = norm\ (P_{load\ i-}P_{PV\ i})$$

The second input variable is the state of charge of the energy storage system normalized to the interval [0, 1], i.e.

$$soc = \frac{Soc_i + Soc_{min}}{Soc_{max} - Soc_{min}}$$

The controller has a single output, flow that determines the volume of power flow between the PV generator, HESS, load, and power grid. The output variable is composed of 15 fuzzy singletons {FI}, ... , {F15}.In order to manage the PV!HESS power flows with just a single output variable, the control strategy implemented by the controller makes the following assumptions: i) all available PV energy is used to satisfy the electrical demand; ii) extra PV energy is either stored to the battery or sent to the grid; iii) outstanding electrical demand is satisfied either from the battery or from the grid; and iv) no power is transferred between power grid and battery. These assumptions correspond to the LP-based solution of the power flow optimization problem. They neglect the power flows that represented only a small fraction of the overall power exchange in the PV IHESS system (i.e. Pbatt-grid) and allow splitting of power between the battery and the grid when there is extra PV energy production. When the PV production is scarce, it splits the residual load between the battery and the grid, prioritizing the local energy storage.

VI. RESULTS

The evolved controller mimics the performance of the system with optimal power flows determined using linear programming. The main goal of designing the fuzzy logic controller was to develop a simple controller that would be easy to implement and understand. Therefore, deterioration of performance w.r.t. to original, optimized system performance was expected. At the same, a significant improvement w.r.t. the baseline (zero) controller was presumed.

Results of simulations involving all three systems confirm these assumptions and show that the evolved fuzzy controller performs comparably well w.r.t. the LP-optimized system, as can be seen from the economical and self-consumption indicators listed in Table 1. In addition, the performance of the LP-optimized system cannot be attained in practice as it would require prior knowledge of all values of load and PV generation for the entire period of operation. On the other hand, in comparison with the baseline controller, the evolved fuzzy logic controller reduced the total RMSE of the power flows by 55.82% and increased the selfconsumption factor by 42.4%.

The performance of a PV /HESS operation strategy can be evaluated through a number of metrics related to the economy and self-sufficiency of the system. In this contribution, economy is gauged by the total cost of energy purchases from and sold to the grid, while the self-sufficiency of the household by the self-consumption factor, ξ, calculated as follows

$$\xi = \frac{P_{pv-load} + P_{bat-load}}{P_{load}}$$

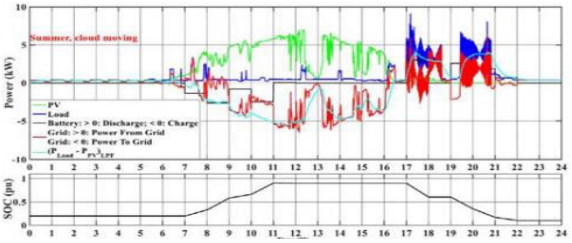
The similarity is evaluated as total root mean squared error (RMSE) between the power flows, which is used as fitness function during the evolution.

Table 1: SYSTEM PERFORMANCE COMPARISON

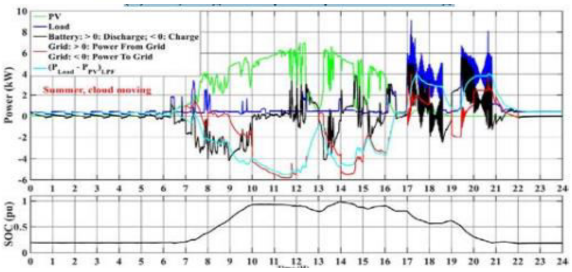
System	LP-optimized	Zero-control	Evo-control
RMSE	0	43702.1	13125.4
C_{buy-E}	$546.8	$1176.2	$820.5
R_{sell-E}	$620.80	$890.78	$526.89
ξ	75.32%	36.71%	65.21%

Influence of power fluctuation smoothing function:

PV and load data on a typical cloud moving day is used to verify the effectiveness of the power fluctuation smoothing function.



(a) Only long-term optimal power scheduling



(b) Combination of long-term optimal scheduling with smoothing function

Fig. 2: Performance of power fluctuation smoothing function

As shown in Figure 2(a), the exchanging power between the PV nano-grid and the main grid severely fluctuates resulting from the power fluctuation of PV due to cloud moving and residential loads. On the other hand, as shown in Figure 2(b), it is observed that the exchange of power between the PV nano-grid and the main grid is smoothed when the smoothing function operates. The battery is used to smooth the power fluctuation of PV and loads by constantly charging or discharging. The battery does not only take action by following the optimal power command but also smooth the power fluctuation in the PV nano-grid.

V. CONCLUSION

This paper develops an optimal energy management of PV grid-connected household nano-grid system by suing logic control. Introduces a fuzzy logic controller implementing PV /HESS energy management based on optimal power flows determined for a real system using linear programming. The power fluctuation smoothing function is introduced to the energy management strategy. The HESS deploys the low and the high frequency power components to the battery and the super capacitor respectively, to relieve the battery lifecycle loss. Simulation results based on practical data have verified the effectiveness of the proposed scheduling approach.

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