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Three-Wire Network: A New Power Supply for Smart Buildings with Demand Management Systems

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ABSTRACT: *This paper presents a new architecture of electric power network for smart building, namely Three-wire Network. The aim of the proposed network is to satisfy the increasingly quality and reliability requirement of power supply, accommodate the on-site renewable energy source, at the same time increase the overall energy efficiency. The paper is then determining the optimal planning of the proposed network: the capacity of the onsite power sources, power converters and energy storage devices, etc. to minimize the total cost during its lifetime. The cost including capital cost, operation and maintenance cost and fuel cost, etc. that occurs at different time is equivalently converted back to the initial stage by an interest rate to form the objective function, called Net Present Cost. The proposed network and formulation is then applied in an illustrative example to show the optimal configuration of Three-wire Network according to the estimation of the electric demand and market price.*

Keywords: *Three-wire Network, Smart building, Distributed Generation, Net Present Cost.*

I. INTRODUCTION

Global warming and climate change have long been a big issue all over the world. As part of Kyoto Protocol, the Europe Union (EU), the United Kingdom (UK) and many other countries have agreed to cut down carbon dioxide (CO2) and other Greenhouse Gas (GHG) emission by 50% by 2050 [1]. To achieve this goal, alternative energy resources including Renewable Energy Source (RES) are expected as an important means to deal with these environmental issues. There is a global target had been set to enhance RES to 20% of the total energy by 2020. On the other hand, it has been recognized that saving energy is even easier and more effective to mitigate the environmental issues. Worldwide, 30 - 40% of all energy is used in buildings, of which a major part is to burn during the operational phase of buildings for heating, cooling, lighting and other appliances. Therefore, saving potential of energy in buildings is huge [2].

Recently, the prevalent use of computer-based appliances requires such a high quality of power supply, i.e., the interruption even in milliseconds can result in a technical and economical issue. For example, we consider the two very common appliances at home: water heater and desktop computer. Water heater consumes a large amount of energy but the interruption with duration of several minutes can be ignored. Differently, computer uses a small amount of power but a millisecond-interruption can cause an extreme loss of data or malfunctioning [3]. This small example shows that nowadays, electrical load is much diverse in both quantity and quality of power supply.

As the above discussion, this paper proposes a new architecture of electric network for smart buildings, called Three-line Network (3-NET). The distinguished feature of 3-NET is to separate electric power supply to different electrical load according to its quality and quantity requirement. Instead of having only an AC supply as traditional, the 3-NET utilizes three independent power network: two DC networks and one AC network, those are connected through controllable power electronic devices. This allows electricity to be transferred between networks, then supply load with the compatible level of quality and quantity, as well as be supplied by the appropriate sources (AC feeder, fuel cell, solar panels, etc.).

The paper is presented as follows. Section II presents the configuration of 3-NET and its important feature compared to the traditional AC network. Section III formulates the operation in both grid-connected and islanded mode. Section IV presents the optimal planning problem for 3-NET with the objective function called Net Present Cost (NPC). Section V is for an illustrative example the proposed method is applied to plan 3-NET for a certain case of electric demand and load profile. Finally, Conclusion is to summarize the important points of the paper and its future work.

II. THREE-WIRE NETWORK

2.1. Traditional AC Network

Traditionally, the electric supplyof a building is simply an AC network that makes connection from the electric feeder to appliances in radius forms.The DC electric consumption, if any, needs rectifiers to be adapted. This means all appliances are providedwith the same level of quality and reliability. As a result, to deal with important loads, power-conditioning technologies are installed such as STATCOM orUninterruptible Power Supply (UPS), etc.

When Distributed Generation(DG) technologies are considered to be used in buildings, for instance solar panels or Photovoltaic (PV) are installed on the roof of the building, and/or Fuel Cell (FC) in the basement, then inverters are needed to wire to AC network. Consequently, the quality problem such as flicker, harmonics, etc. associated with the switching operation may occurs.

Intuitively, traditional AC network is simple in planning and operation but suffering from many problems due to the high level of reliability requirement and power electronic conversion devices: high installation cost, power and/or data losses.

2.2.Three-wire Network Configuration

Addressing the above-mentioned problem of the traditional power supply, 3-NETconsists of three power networks: (1)high quality DC, (2) low quality DC and (3) AC network as shown in Fig. 2. These networks are interconnected through appropriate controllable power electronic devices.

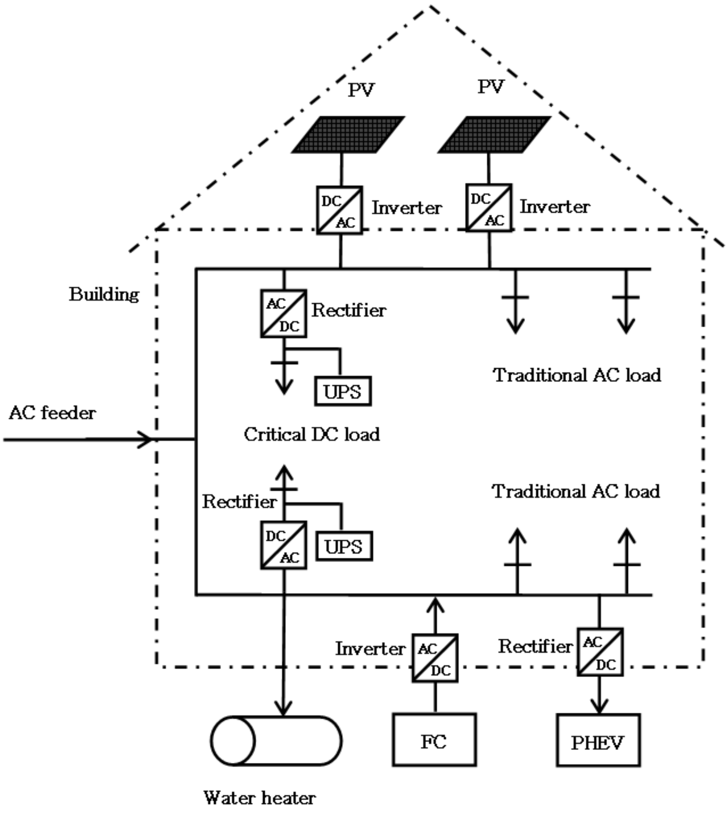

Fig. 1. The traditional AC network with the onsite DG sources.

The idea of 3-NET is to customize the quality and quantity requirement of various electric loads while to adapt the onsite DG sources which are mostly generating DC power in nature. The high quality DC network is to supply critical loads such as computer, electronic appliances, etc. which consumes DC electricity in nature with a small amount but requires a very high quality level. This network is fed by both AC feeders and battery bank for reliability improvements. The low quality DC network, on the other hand, is to supply the thermal loads, e.g., water heater, which can use both AC and DC electricity with large quantity but minutes-interruption may not be realized. Intermittent DG sources (PV) can be wired directly or through a simple DC/DC converter to this network; the excess power can be charged to battery for later use (either in high or low quality network). AC network, like traditional power supply, is fed by AC feeder to serve AC loads, e.g., AC motors.

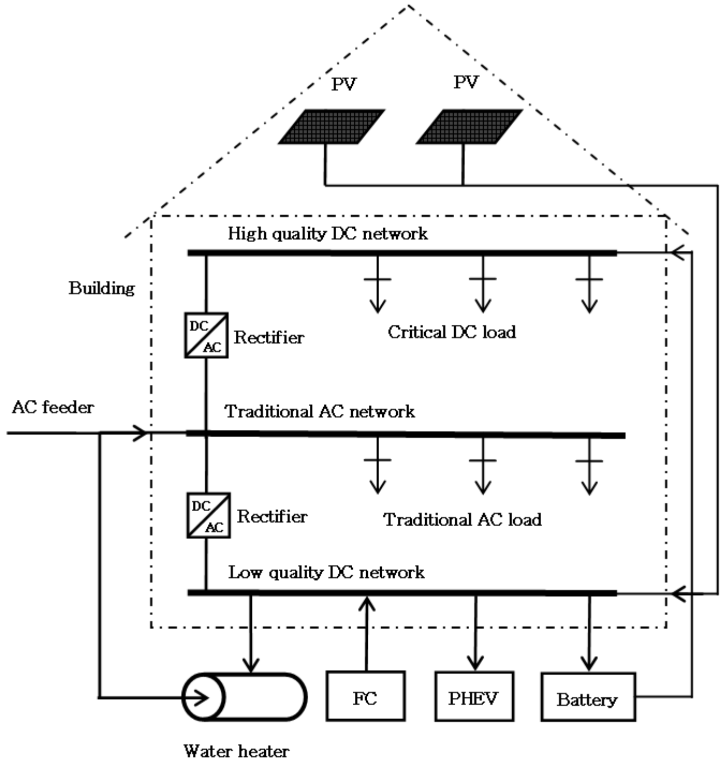

Fig. 2. The proposed 3-NET with DG sources in smart buildings

With this feature, 3-NET is expected to serve a platform for both onsite DG sources and load requirements. The following are the advantages of 3-NETcompared to traditional power supply:

Reduce the installation cost power electronic devices because only two centralized rectifiers are needed for AC/DC conversion in 3-NET.

Improve the satisfaction of loads by customizing the load requirements into AC/DC loads, critical, non-critical and AC loads.

Reduce power losses by avoiding intensive use of power electronic devices to AC/DC and DC/AC conversion.Accommodate various DG sources: controllable and uncontrollable sources (PV).

III. THREE-WIRE NETWORK OPERATION

3.1.Grid-connected Operation

Normally, 3-NET is supplied both from the electric grid and its own sources.The operation of PVis dependent on the weather condition such as solar radiation, temperatureand humidity; it is called uncontrollable or non-dispatchable sources. On the other hand, AC feeder and FC can be adjusted during operation to meet the demand, thus, called controllable or dispatchable sources. The difference is only that FC'soutputvaries within a technical range (minimum to maximum)which is associated with a fuel cost modelled as a quadratic function.Thepower supply of AC feeder can be negative or positive that is equivalent to the case when 3-NET provide or consume energy from the grid. The electricity cost is simply as product of quantity and price.

In 3-NET, the AC network is fed by AC feeder to serve AC loads(rotating machines) such as ventilation, pumping systems,etc. This kind of loads requires AC power in nature to provide magnetic fields in rotor and state cores; the reliability is provided the same as the electric grid, for example 0.99. The high quality DC network is to serve the critical load with very high reliability requirements (0.999). It is supplied by AC network through an appropriate controllable rectifier in coordination with a battery bank as buck up sources. Battery also can be used to store the energy excess from the low quality DC network. Finally, the low qualityDC network is fed by PV, FC and AC network to serve DC load that does not require high level of reliability, is interruptible or reschedulable. For example, Plug-in Hybrid Electric Vehicle (PHEV)can be plugged and charged any moment during the night time; the only requirement is being full charged when being used in the morning of the next day. Another example is water heater, it can be fed both from the low quality DC network to utilize the freeenergy from PV (if available) and from AC network when theelectricity price is low. In grid-connected, battery is fully charged and serve when there is an interruption of the AC feeder.

3.2. Islanded Operation

In case of emergency when the AC feeder is lost, battery bank will discharge to serve the critical DC load, by this means, increasethe reliability of power supply (0.999). Therefore, the battery bank must be capable to fulfill all the demand of critical DC loadsduring interruptions. To determine the needed capacity of battery bank, we will consider interruption probability of the AC feeder as follows.

Let us define:

P(int, t) is the probability of interruption which has duration of t (second).

P(int, t_{int}>t) is the probability of interruption which has duration is larger than t (second).

$$P(\text{int}, t_{\text{int}} > t) = \int_t^{\infty} P(\text{int}, t) dt \quad (1)$$

If the reliability of AC feeder is 0.99, then

$$P(\text{int}, t_{\text{int}} > 0) = 1 - 0.99 = 0.01 \quad (2)$$

To increase the reliability up to 0.999, battery bankmust be able to supply the critical DC load during interruptionswith the durationsmaller than t_1, as follows:

$$P(\text{int}, t_{\text{int}} > t_1) = \int_{t_1}^{\infty} P(\text{int}, t) dt = 0.001 \quad (3)$$

The capacity of battery bank can be calculated as

$$E_{bat} = L_{crit,\max} \cdot t_1 \quad (4)$$

whereE_{bat} is the battery bank capacity, [kWh] or [MWh]; $L_{crit,max}$ is the maximum critical load, [kW] or [MW]; t_1 is maximum duration of interruption can be covered by battery bank, [h].

IV. THREE-WIRE NETWORK PLANNING

4.1.Objective Function

The objective function is to minimize the total cost of the lifetime, i.e., NPC which is the sum of all the cost incurred during its lifetime after converted into present cost at the initial stage: Capital cost, replacement cost, operation and maintenance cost and fuel cost, etc.

$$NPC = \sum_{t=0}^{T} \frac{1}{(1+r)^t} C_t \quad (5)$$

whereC_t is the cost at the stage t of the lifetime, called net cost flow, [$]; r is the interest rate, [pu]; and T is the project lifetime, [year].

The net cost flow C_t is the sum of the cost of all sources at time t, including capital cost, replacement cost, O&M cost, fuel cost and/or payment for purchasing electricity from the market.

$$C_t = \sum_{i=1}^{N} (C_{0it} + C_{Rit} + C_{OMit} + C_{Fit}) + C_{Et} \quad (6)$$

where$i$ is the DG unit, N is the total number of DG; C_{0it} is the capital cost of DG unit i at stage t, [$]; C_{Rit} is the replacement cost, {$]; $C_{O\&Mit}$ is the operation and maintenance cost, [$]; C_{Fit} is the fuel cost, [$]; and C_{Et} is the electricity cost, [$].

4.2.Optimal Operation

In planning, there is a short-term operation problem must be considered to determine the optimal operation of a day: i.e., minimizing the fuel cost at each hour while satisfyingthe load's demand. The problem can be formulated mathematically as follows [6-8].

$$C_{Ft} = \min_{P_{Gi}, P_{Et}} \left\{ C_i(P_{Git}) + \rho_t P_{Et} \right\} \quad (7)$$

Subject to

$$P_{Dt} = \sum_{i=1}^{N} P_{Git} + P_{Et} \quad (8)$$

$$P_{Gi}^{\min} \le P_{Git} \le P_{Gi}^{\max} \quad (9)$$

$$C_i(P_{Git}) = c_i + b_i P_{Git} + a_i P_{Git}^2 \quad (10)$$

where $C_i(P_{Git})$ is the fuel cost of DG units i, [$]; P_{Git} is the power generation at time t, [kW] or [MW]; ρ_t is the electricity price, [$/kWh] or [$/MWh]; P_{Et} is the electricity purchased from the market, [kWh] or [MWh]; P^{min}, P^{max} are the limits of DG unit, [kW] or [MW]; a_i, b_i and c_i are the coefficient of fuel cost, [pu].

In the above formulation, equation (7) is the objective function of the daily operation, i.e., determining the generation of DG units at each hour to minimize the fuel and electricity cost. Equation (8) expresses the balancing of supply and demand. Equation (9) is the generation limits of DG units. Finally, equation (10) is the fuel cost model of DG units as a quadratic function of power output.

V. ILLUSTRATIVE EXAMPLE

This section presents an illustrative example of 3-NET for a smart building. In this case,it is assumed that the data of planning is available: The electrical demand, load profileand solar radiation, etc. This is to calculate the fuel cost of the existing 3-NETto satisfy the load in the typical dayof summer and winter in a year. The electricity price is also estimated in summer and winter, this give choices for 3-NET to be whether self-provided by the onsite DG sources or purchasing from the market. The lifetime of 3-NET under consideration are 10 years. The problem was coded in MATLAB software and run in a Core i3 2550M computer. The result is presented in the following.

Table 1 shows the optimal design of 3-NET in the increasing NPC order. The best configuration is with 6 FC units (120 kW), 7 PV units (140 kW) and 4 rectifier units (80 kW). In this 3-NET, PV is operated with a Maximum Power Point Tracking (MPPT) control scheme which allows PV to generate as much power as available from solar radiation; take advantages of free fuel energy. FC is operated in coordination with the market price of electricity; if the price is high, FC will be controlled to generate more, avoiding the purchase of expensive energy from the market. Inversely, if the price is low, more electricity is purchased from the market, FC will be controlled to produce less.

Table1. Economical Evaluation of Potential 3-NET Configuration

Case number	NPC	DG sources capacity (x 20 kW)		
		Fuel cell	Photovoltaics	Rectifier
1	8476.539	6	7	4
2	8477.635	6	6	4
3	8478.864	6	5	4
4	8480.128	6	4	4
5	8482.325	6	7	5
6	8483.282	6	6	5
7	8483.313	7	7	3
8	8484.354	6	5	5
9	8484.467	7	6	3
10	8485.471	6	4	5
…	…	…	…	…

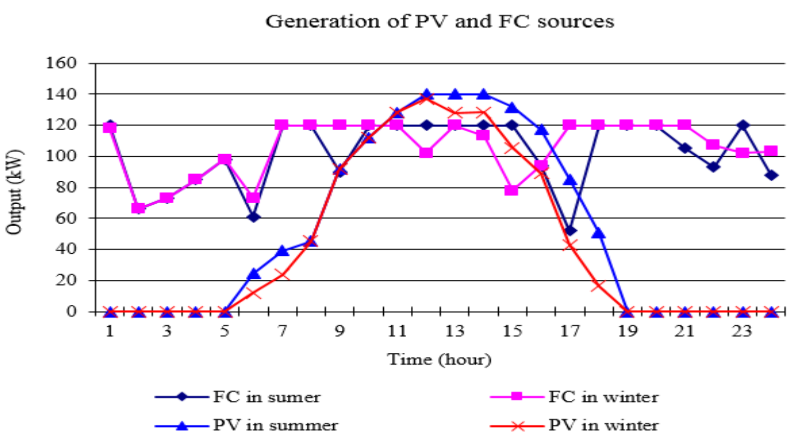

Fig. 3. The operation of PV and FC in a typical summer and winter day.

Fig. 3 shows the operation of FC and PV in a typical summer and winter day. In 00:00 – 05:00, there is no solar radiation and the electricity price is low, FC generates from 60 to 100 kW. In 06:00 – 15:00, the price of electricity is higher, FC seems to generate with all maximum available capacity (120 kW), PV generates with the available solar resources. In 19:00 – 24:00, the price become lower and solar radiation is not available, the generation also reduced.

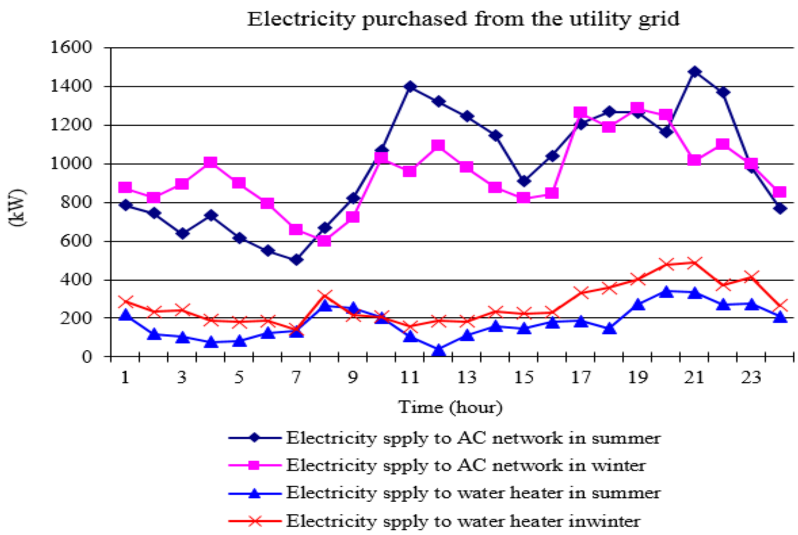

Fig. 4. The electricity purchased from the market to serve the traditional AC and water heater load.

Fig. 4 shows the electricity purchased from the market in typical summer and winter day. It is clear that the AC load is served by the AC feeder thoroughly while the water hear is both served by the low quality DC network and AC feeder. The power from the FC and PV is to supply directly this load; the shortage is supplied by AC feeder; the excess, if any, is charged to battery bank for usage in emergency.

VI. CONCLUSION

This paper has made discussion on the energy problem and its consequence in environments, which encourages the use of green energy, e.g., solar, and other alternative energy sources. In addition, the evolution of electronic technology has changed the electrical properties of loads. There are various electrical appliances with different quality and quantity requirements of the power supply. Therefore, the proposed 3-NET is expected serve as a platform in smart buildings in near future to both accommodate the use of onsite DG sources and meet the reliability requirement properly. The structure and operation of 3-NET were presented in details in the above. Then, the formulation of the optimal planning of 3-NET was discussed and applied in an illustrative example. Battery sizing and DG capacity were determined in Table 1 with the objective function, i.e., NPC. The daily operation of the optimal planning was presented in Fig. 3 and 4. In future, we will examine further the feasibility and technical relevance of 3-NET with more up-to-date technology and data.

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