Applications of Sequential Power Flow Analysis for High and Low Voltage Distribution Systems to Energy Loss Evaluation for Dwelling Units or Buildings

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Abstract

In this paper, a sequential power flow calculation method for high- and low-voltage distribution systems is proposed. The proposed method is employed to assess the energy losses for a single-phase, 3-wire, 2×110V branch circuits of a typical dwelling unit. The daily, weekly, monthly and annual energy losses of a dwelling unit are obtained by a succession of precise power-flow analyses considering the daily and seasonal use of lighting and typical electrical appliances in a dwelling unit. Based on numbers of dwelling units or households and detailed analysis results of their power consumption, the energy losses, financial loss and carbon emissions of dwelling units in Taiwan are presented. The outcomes are of value to residential and commercial buildings for energy conservation and the implementation of sustainable development policies in Taiwan.

Keywords: Distribution System, Energy Loss Evaluation, Power Flow Analysis, Global Warming.

1. Introduction

Nowadays, the efficient use of energy resources has become an essential element for rapid progress of industry and commerce. Most energy resources used by people are derived from nature. For a long time, the harmony between humankind and nature has been maintained. The human population has increased markedly since the industrial revolution. The demands of energy resources become more and more obvious. However, the use of natural resources has a significant effect on the environment.

Taiwan is a mountainous island situated in a subtropical zone. It depends on imports for approximately 97.9% of primary energy [1]. At present, the applications of solar power, wind power, biomass power, geothermal power, small hydro-power, tidal power and other renewable energy generation are continually promoted in Taiwan. On the other hand, the problems caused by the use of energy resources can be divided into three parts: (1) Energy Production, (2) Energy Transmission, and (3) Energy Consumption. In this paper, the ranges between energy transmission and energy consumption, including line losses of primary and secondary distribution power systems, are discussed. As well, the characteristics of home appliances are all taken into consideration in the proposed method.

In 2001, the electricity consumption in residential sector was about 26% of the total electricity energy used in Sao Paulo State, Brazil [2]. In 2004, the residential electricity consumption was about 29.24% of total electricity consumption in the EU-15 [3]. In addition, the residential energy consumption in the UK has consumed 28% of the total energy use, and the residential energy consumption in the USA was 22% of the total energy demand [4]. In 2006, the residential and commercial energy consumptions in Malaysia were 13.6% of total energy use [5]. In Taiwan, the residential sector consumed 44.4 billion kWh in 2011, which equivalent to 18.33% of the total energy consumed [6]. Residential electricity consumption in Taiwan is shown in Fig. 1.

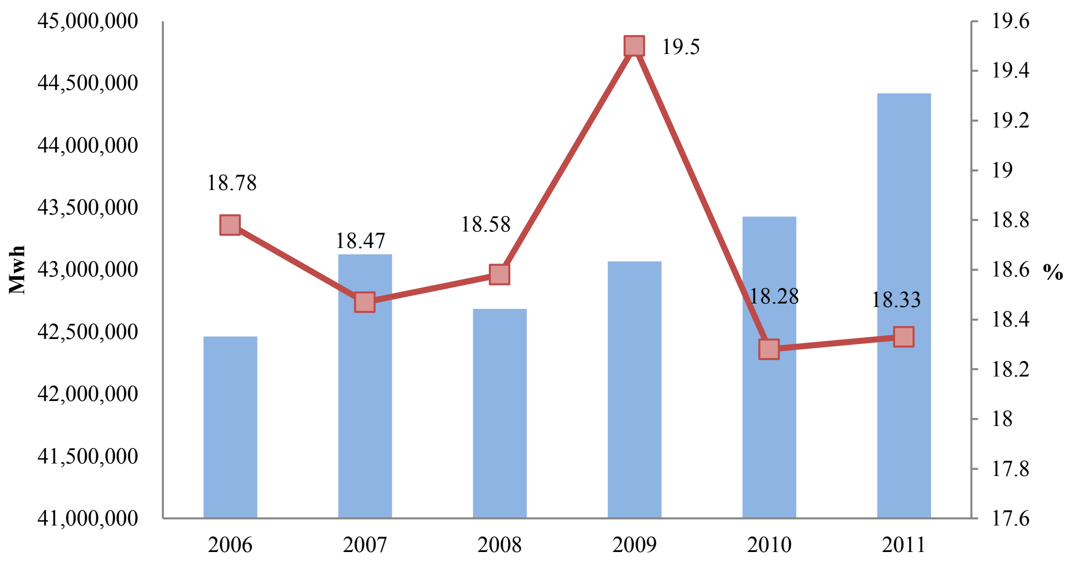

Fig. 1. Residential electricity consumption in Taiwan

To improve the energy efficiency of power systems, an effective method for evaluating energy losses is required [7]. The existing energy loss estimation methods can be used to assess energy losses in large systems in a precise way, but they are not suitable for estimating the annual energy losses in branch circuits or feeders of households or buildings [8]. In a household, various home appliances often are connected with branch circuits. Because the power consumption behaviors of the electrical home appliances may change time to time, they may have a considerably effect on the accuracy of loss evaluations for low-voltage distribution systems. In low voltage distribution systems, especially in branch circuits or feeders, the system topologies and power consumption behaviors of each load should therefore be reflected. Unfortunately, the existing probabilistic energy loss estimation methods cannot take into account the real characteristics of the small load variance in low voltage distribution systems.

In this paper, a sequential power flow method for high- and low-voltage distribution power systems is proposed to assess the energy losses of branch circuits or feeders by considering the system topologies and power consumption behaviors of home appliances along the circuits. The proposed method is employed to assess the total energy loss of typical residential distribution systems in Taiwan.

2. Sequential Power Flow Method for High and Low Voltage Distribution Systems

In the existing power flow approaches, the distribution transformers and their loads are integrated and are tapped off the primary mains. The power losses in secondary distribution systems are ignored. In practical terms, with the wide coverage of distribution networks, any gain in saving energy could tremendously improve the operation efficiency of a distribution system. That is, the line losses in residential or commercial distribution systems cannot be neglected. The flow chart of the proposed sequential power flow method for high- and low-voltage distribution systems is shown in Fig. 2. The solution procedure of the proposed method is described below, step by step:

Step 1. Set initial node voltages and form K matrix directly from input data for primary and secondary distribution systems.

Step 2. Calculate node injected currents, branch voltages and update node voltages for primary distribution systems.

Step 3. Set initial node voltages, calculate node injected currents and update node voltages, and compute the total node injected currents for secondary distribution systems.

The iterative process of the proposed method is continued until the residuals of the bus voltages are all less than a specified tolerance.

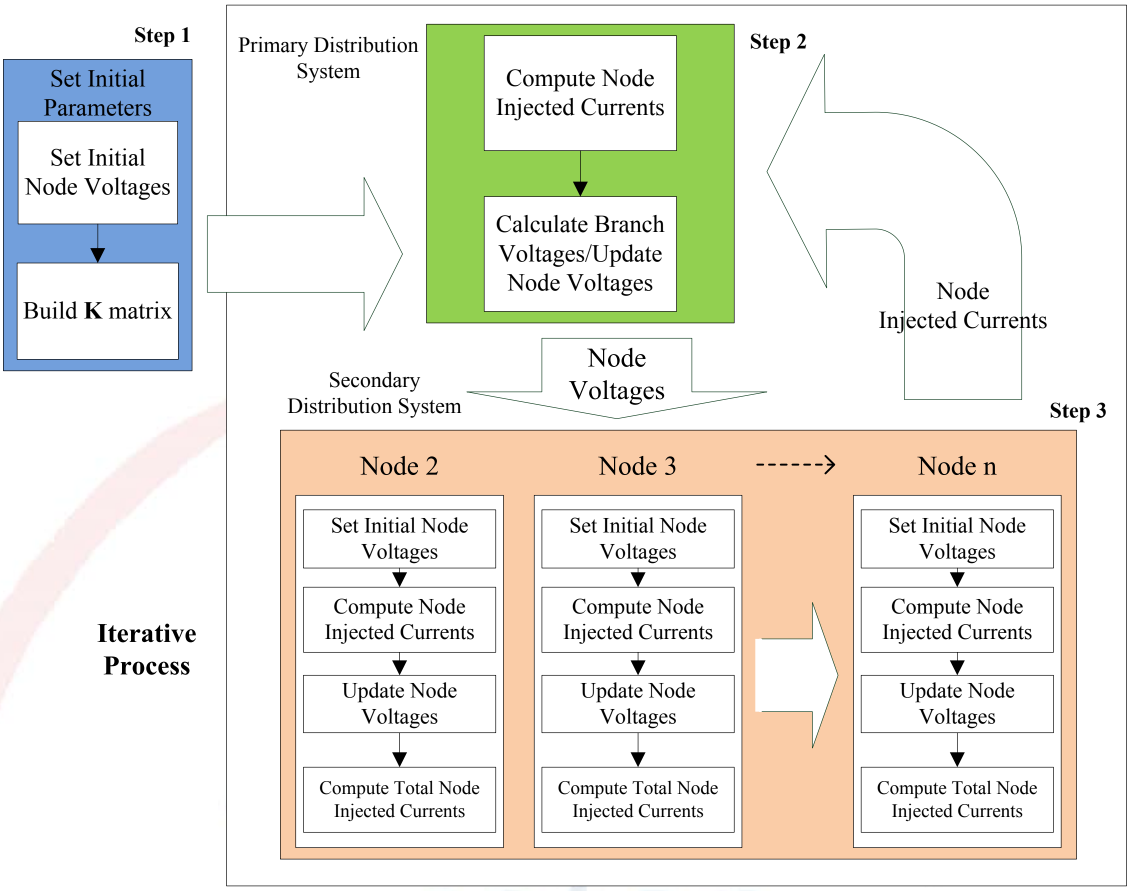

Fig. 2. Flow chart for sequential power flow solutions

3. Energy Loss Estimation Method for Low Voltage Distribution Systems

Because the branch circuits of a household or building are located in the most downstream portions of power system, the energy losses of branch circuits or feeders of households or buildings should be evaluated in detail or the whole system energy losses cannot be estimated accurately. In this paper, an effective method is proposed to estimate the energy losses of the branch circuits or feeders of a home or building.

Considering the system topologies and power consumption behaviors of small home appliances along branch circuits or feeders, the proposed method can estimate the real power for each time interval first, followed by daily, weekly, monthly and annual energy loss estimations [9]. In other words, to perform annual energy loss estimation, the four steps of power-flow calculations are required, such as: (1) daily power-flow calculation (DPFC), (2) weekly power-flow calculation (WPFC), (3) monthly power-flow calculation (MPFC) and (4) annual power-flow calculation (APFC).

To take into consideration the daily and seasonal use of various kinds of small home appliances, several sets of typical daily-load curves (DLCs) have been generated. In the proposed method, 16 DLCs are required to describe the real and reactive power consumption behaviors for each kind of home appliance. The schematic diagram of the energy loss estimation is shown in Fig. 3.

For a specific network topology, operating and loading condition, three-phase power-flow calculation can be employed to determine the system electrical parameters [10]. At any instant, real power loss in each line segment can be estimated by a three-phase power-flow calculation. Extending for an accurate power-flow calculation, a precise annual power-flow calculation can be determined.

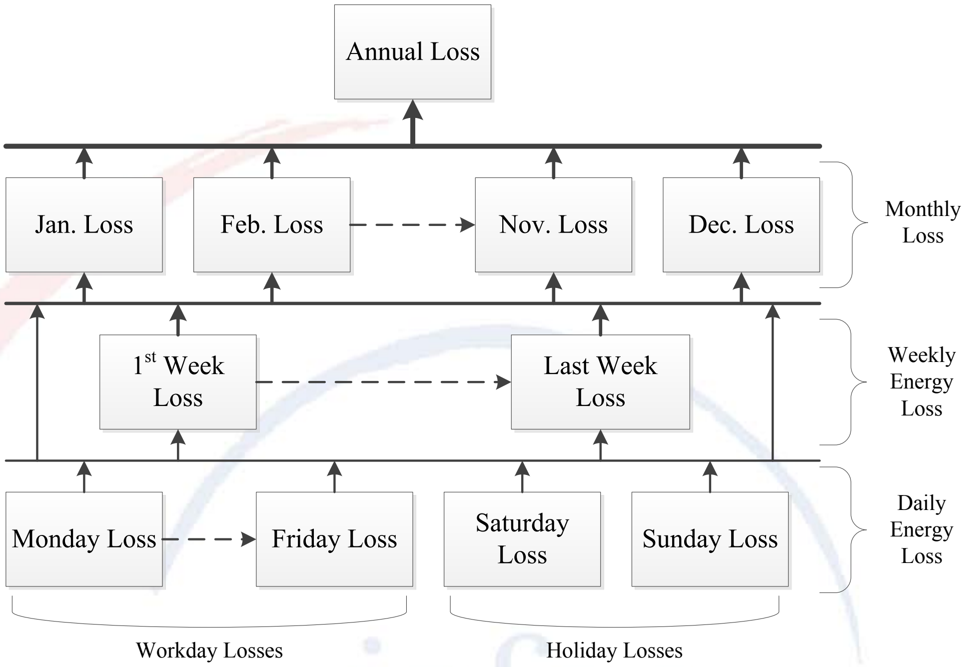

Fig. 3. Energy loss estimation scheme for low voltage distribution system

3.1 Daily energy loss estimation

In order to accurately assess a daily energy loss, the daily use of electric home appliances along branch circuits or feeders should be reflected. In the proposed method, a set of 16 DLCs is developed for each kind of electric home appliance. Several sets of the typical DLCs are required to be created for all kinds of electric home appliances. The daily and seasonal use of electrical home appliances may vary from time to time, day to day, and season to season. Therefore, the changes in power consumptions of electric home appliances all should be considered. In order to assess the daily energy loss accurately, the load survey is required to develop the typical DLCs for each kind of electrical home appliance. Moreover, the time intervals for DLCs will affect the accuracy and computing time of power loss estimation. In other words, the longer the time interval, the lower the accuracy of the estimation results and the less computing time will be obtained. In this paper, the time interval of 15 min was adopted. That is, there are 96 time intervals in each DLC. To perform daily energy loss estimation, the 96 instantaneous power loss estimation results are summed up.

3.2 Weekly energy loss estimation

The daily and seasonal use of electrical home appliances may be different from workdays to holidays. The DLCs are distinguished into the power consumption characteristics of workdays and holidays in a week. In general, the workdays are from Monday through Friday. The weekly holidays are Saturday and Sunday. In other words, there are 5 workdays and 2 holidays in a week. The weekly energy loss can be estimated by considering the distinct power consumption characteristics between workdays and holidays.

3.3 Monthly energy loss estimation

By summing up the proper daily or weekly energy losses of the concerned month, the monthly energy losses can be determined. For a certain year, the numbers of days in different months may be different. In a common year, there are 365 days and there are 28 days in February. On the other hand, in a leap year, there are 366 days and there are 29 days in February. To simplify the discussion, the numbers of days for all months are assumed to be 30 days, and are assumed to be 21 workdays and 9 holidays.

3.4 Annual energy loss estimation

The daily and seasonal use of electrical home appliances may have significant differences among the four distinct seasons. For different seasons, different DLCs should be obtained for the same electrical appliance. Besides, the different power consumption behaviors of electrical home appliances on workdays and holidays should be taken into consideration as well. That is, the daily and seasonal use of electrical home appliances should all be considered.

In order to perform annual energy loss estimation, 8 typical daily energy loss estimations are necessary, such as: (1) Spring Workday, (2) Spring Holiday, (3) Summer Workday, (4) Summer Holiday, (5) Fall Workday, (6) Fall Holiday, (7) Winter Workday and (8) Winter Holiday. By arithmetic calculations using 8 typical daily energy losses by the proper number of days, the annual energy loss can be estimated. Also, the annual energy loss can be estimated by using the proper monthly power loss.

The proposed sequential three-phase power-flow calculations can be employed to estimate the system electrical parameters for a day, a week, a month or a year. The results of the power flow calculations can be employed to examine the strategies of system operations. To provide high quality power to consumers, the results of the power flow calculations can also be employed to review the requirements of voltage regulation and control of the feeders. Depending on the short-term and long-term load forecasting and feeder load management, the overloading problems for feeders and transformers can therefore be avoided. In the next section, the proposed sequential three-phase power-flow calculation will be employed to estimate the annual energy losses of the typical residential distribution system in Taiwan.

4. Energy Loss Estimation for Typical Residential Distribution Systems in Taiwan

In Taiwan, most of the households are served by a 1Φ3W 110/220V system with two phase conductors, one neutral conductor and one grounding conductor. The voltages of two 110V phase conductors are out of phase by 180°. The 110V and 220V rated electrical appliances can all be served by this system. The lighting and lower-power consumption appliances are fed by the 110V branch circuit. Moreover, the higher-power consumption appliances are all served by the 220V branch circuit. The parameters and partial data for the sample system shown in Fig. 4 are tabulated in Table 1. This typical household wiring system consists of 10 branch circuits and 2 spare circuits.

Circuit #1 and Circuit #2 are used to serve home lighting branch circuits. Circuit #3 to Circuit #6 are used to serve receptacle branch circuits. Circuit #7 is an individual branch circuit for kitchen appliances. Circuit #9 to Circuit #11 are used to feed individual branch circuits for air conditioners. Circuit #8 and Circuit #12 are spare circuits. Many sets of typical DLCs are used, but only the typical DLCs for summer workday are shown in Figs. 5 and 6.

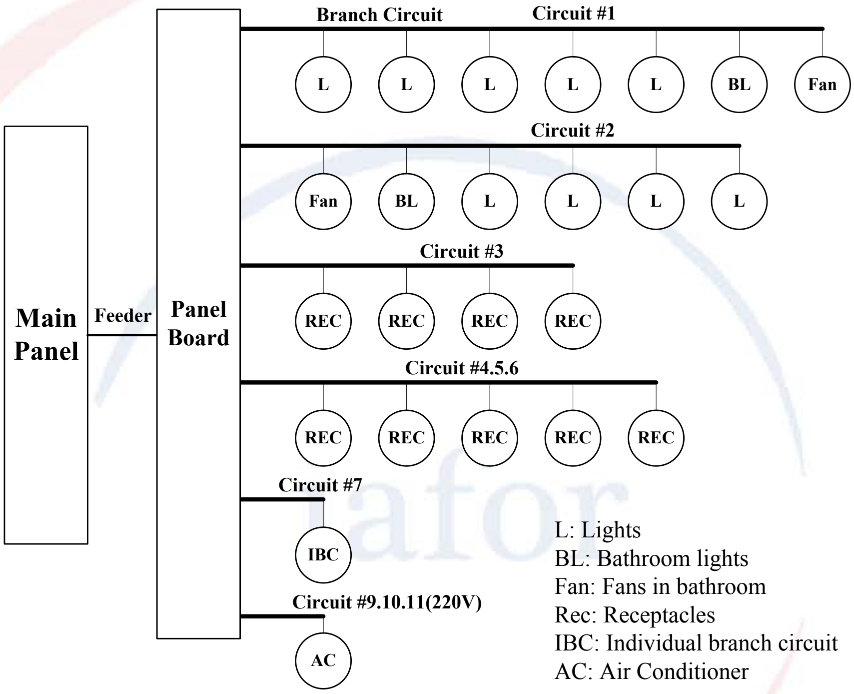

Fig. 4. One line diagram for typical residential distribution system

Table 1. Parameters and partial data for sample system

	Lights	TV	Refrigerator	Air conditioner
P(W)	180	150	91	1600
Q(var)	159	132	78	1200

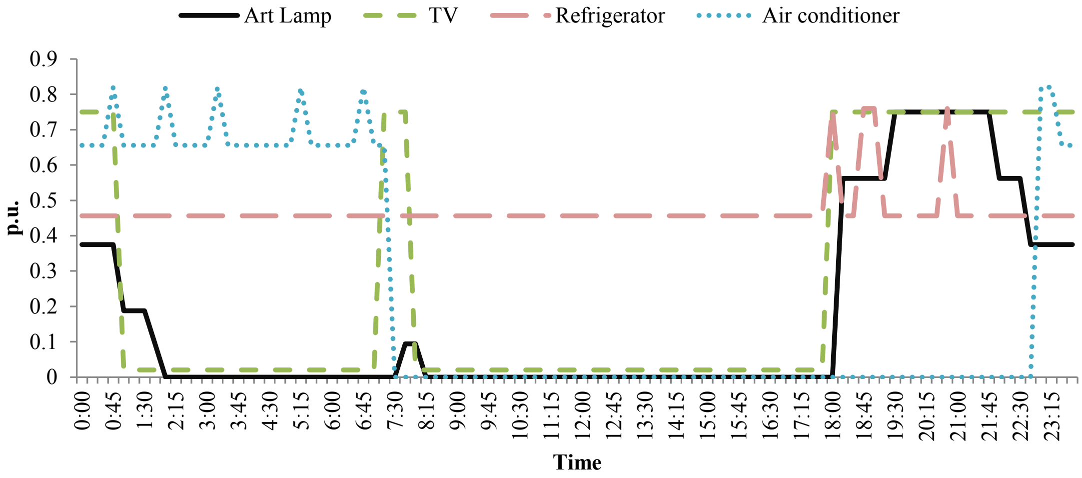

Fig. 5. Typical DLCs of active powers for summer workday

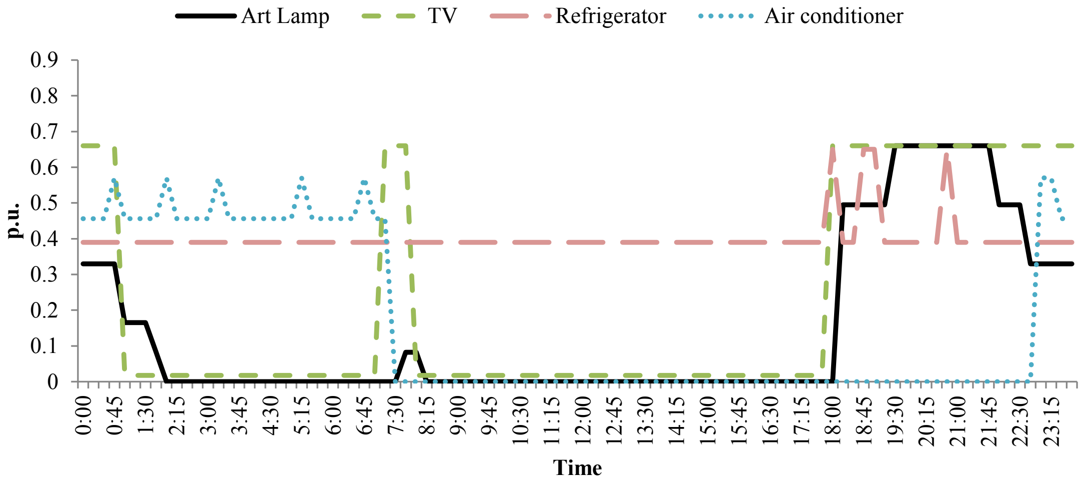

Fig. 6. Typical DLCs of reactive powers for summer workday

In this paper, the electrical home appliances are all shown as injected currents. Furthermore, by considering the system topologies and power consumption behaviors of electrical home appliances along circuits, the proposed sequential power-flow method can estimate the energy loss accurately. The daily, weekly and monthly energy losses are shown in Figs. 7, 8 and 9, respectively. As can be seen from Table 2, the workday energy loss, holiday energy loss, weekly energy loss, monthly energy loss and annual energy loss can be obtained.

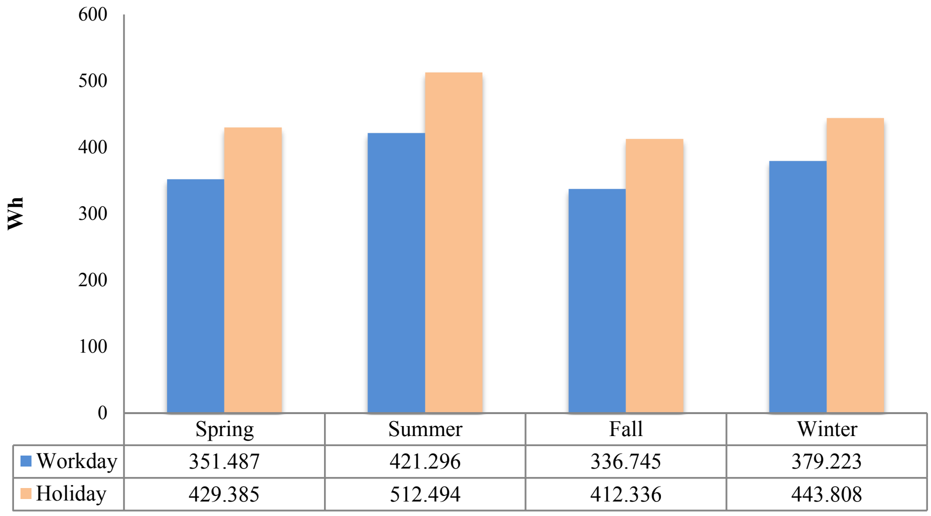

Fig. 7. Daily energy losses for four seasons

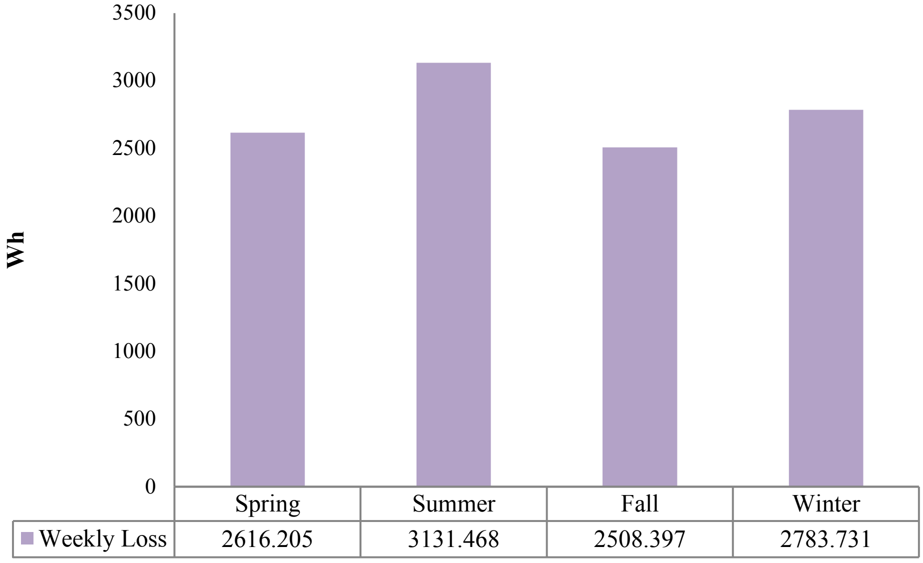

Fig. 8. Weekly energy losses for four seasons

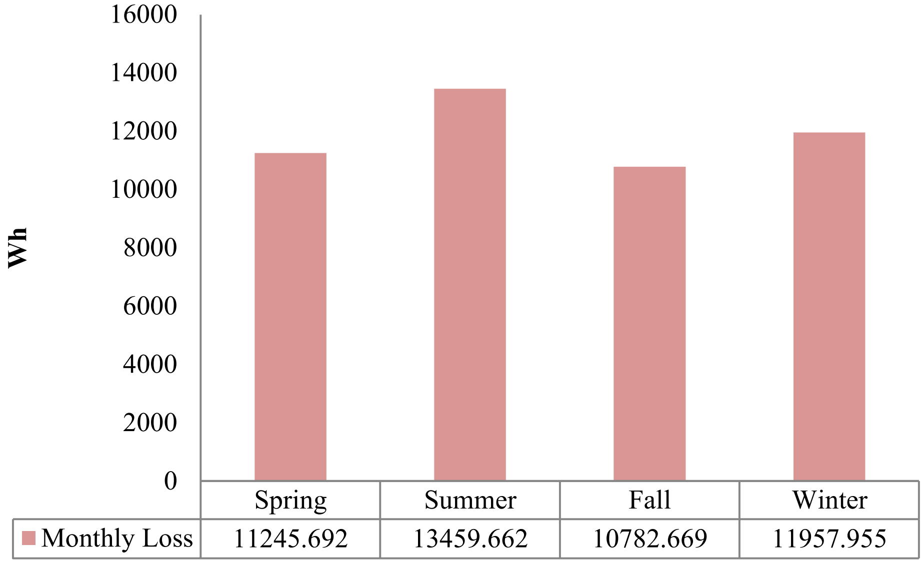

Fig. 9. Monthly energy loss for four seasons

Table 2. Energy losses for four seasons

	Spring (Wh)	Summer (Wh)	Fall (Wh)	Winter (Wh)	Annual (kWh)
Workday	339.486	461.478	334.776	428.162	
Holiday	403.882	553.23	398.246	450.02	
Weekly	2,505.194	3,413.85	2,470.372	3,040.85	
Monthly	10,764.144	14,670.108	10,614.51	13,041.582	
Annual					147.271

The annual energy loss is around 147 kWh per household. The energy loss for the summer season is about 44kWh. If the average price of electricity for the summer season is 4.5 NTD (New Taiwan Dollar)/kWh, the cumulative electricity price for the summer season is 198 NTD. On the other hand, the energy loss for the non-summer seasons is about 103 kWh. If the average price of electricity for the non-summer seasons is 4.0 NTD/kWh, the cumulative electricity price for the non-summer seasons is 412 NTD. The cumulative cost of the annual energy loss for a single residential user is 610 NTD.

According the 2007 Taiwan Bureau of Energy Annual Report, an emission factor for CO_2 is 0.637 kg-CO_2 /kWh. Therefore, the extra CO_2 emission for a typical residential distribution system is 93.42 kg/year per household.

According to the 2011 Taiwan Power Company (Taipower) annual report, the number of households in Taiwan is round 12.76 million. Therefore, the total CO_2 emission of the residential distribution system, caused by energy losses, is up to 1,192,958,000 kg. In terms of economic losses, the cumulative electricity consumption of the energy losses is up to 1,875,720,000 kWh. That is, the cost of energy losses in residential distribution systems is about 7,783,600,000 NTD. The cumulative energy consumption and CO_2 emission are shown in Table 3.

Table 3. Cumulative energy consumption and CO_2 emission

	Energy losses (kWh)	Cost of losses (NTD)	CO_2 emission (kg)
Single user	147	610	93.492
12.76 million users	1,875,720,000	7,783,600,000	1,192,958,000

5. Conclusions

In this paper, the sequential power-flow method has been proposed for evaluating energy losses in branch circuits and feeders for primary and secondary distribution systems. In the proposed method, the system topologies and the characteristics of home appliances all can be taken into consideration. By using the proposed sequential power flow method for high- and low voltage distribution systems, the annual energy loss can be estimated in an accurate way. The results of this paper are of value to residential and commercial building in designing the finest energy-saving wiring designs, improving system efficiency, and therefore, reducing the carbon dioxide emissions.

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