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(Short Communication)

A Time-Oriented Approach for the Load-Shedding Design in an Isolated Power System

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ABSTRACT

A time-oriented approach to load shedding design of an electrical power system is proposed in this paper. To overcome the coordination difficulty among under-frequency relay settings, the time-oriented concept has been incorporated into the proposed scheme. Meanwhile, to decrease the possibility of load-shedding failure caused by distinct system dynamics, a modification method that considers maximum deviation of frequency at the last load-shedding step has also been added into the scheme. Using this method, the total amount of load to be shed can be calculated more accurately. The decline of the system frequency can be also better grasped. Numerical simulations have been performed to verify the effectiveness of the proposed method.

Key Words: time-oriented approach, initial rate of change of frequency, load shedding, under-frequency relay

I. Introduction

When a significant disturbance occurs, such as loss of a large generator, disconnection of a heavily loaded transmission line, or failure in any component of the system, it often results in imbalance between power generation and load demand, thereby driving down the system frequency. To arrest the fall in the system frequency and keep the system from collapsing, load shedding is necessary. The main objective of the load-shedding scheme is to shed a pre-determined amount of load through several shedding steps such that energy balance can be quickly achieved (Concordia *et al*., 1995; Thompson and Fox, 1994). A proper load-shedding design scheme can help minimize the degree of customer disruption and balance the load for the remaining generations in a short time.

In recent decades, different methods have been proposed for appropriate load-shedding schemes either for interconnected systems or isolated systems. One of them is a scheme for under-frequency load-shedding (Shilling, 1997; Prasetijo *et al*., 1994; Lokay and Burtnyk, 1968). Although this scheme has advantages in terms of simplicity and speed, its drawbacks, including difficulty in shedding an appropriate amount of load and the necessity of handling the coordination problem, may largely countervail these merits. Based on use of the rate of change of frequency, a load-shedding scheme was also suggested (Grewal *et al*., 1998; Girgis and Peterson, 1990). However, this method suffers from the same drawbacks as the load shedding scheme with under-frequency relays. Recently, an adaptive load-shedding methodology was employed based on the initial rate of change of frequency at the relay (Anderson and Mirheydar, 1992). This method has been found to be feasible; however, it requires tedious computations to reach a solution. With the emergence of computational intelligence technology, this approach has been effectively applied to load-shedding problems. To accelerate computation, neural networks have been utilized during a forced outage of a generation unit (Djukanovic *et al*., 1993; Kottick and Or, 1996). To cope with uncertainties in identifying power system disturbances, an extended fuzzy reasoning algorithm has also been adopted (Tso *et al*., 1997). The reported test results indicate good potential for this application.

In power relaying, an under-frequency relay is incorporated with a time delay in order to curtail the impact of unexpected surges. However, such a time delay may lead to a longer trip-reaction time, and the frequency may decline at the same time, thereby leading to unnecessary trips of generator protective relays. To deal with this problem, a time-oriented approach is proposed in this paper. In this scheme, detection of the initial rate of change of frequency with predetermined time intervals is employed as the basis for making load-shedding decisions. Based on the maximum change of frequency at the last shedding step, a modification process added to the proposed load-shedding algorithm is embedded such that the load-shedding performance can be further improved (Huang and Huang, 2000). In this way, variation of the system frequency can be more effectively arrested. The difficulty of coordination among frequency relays can also be easily solved. Numerical simulation results support verify the effectiveness of the proposed method.

II. Mathematics Formulation

An analytical approach to the investigation of power system dynamics is examined in this section, based on the idea of average or uniform frequency response behavior. A block diagram with a feedback loop, including a speed governor model, turbine model and generator-load model, is shown in Fig. 1. It can be used to analyze the system frequency response when there is any decrease in generation or a sudden increase in load. In this figure, $\Delta P_r(s)$ and $\Delta f(s)$ individually represent the variation of the reference power and system frequency, respectively. $\Delta P_g(s)$, R, T_g, and K_g represent the input power increment, speed regulation, time constant, and gain in the speed governor system, respectively. $\Delta P_t(s)$, T_t and K_t stand for the output power increment, time constant and gain of the turbine, respectively. $\Delta P_d(s)$, H and D correspond to the load demand increment, system inertia and load reduction factor of the generator-load model, respectively. Units of T_g, T_t and H are expressed in seconds, D and R in p.u. MW/Hz, $\Delta f(s)$ in p.u. Hz, and $\Delta P_r(s)$, $\Delta P_g(s)$, $\Delta P_t(s)$, and $\Delta P_d(s)$ in p.u. MW. Note that the generator-load model shown in Fig. 1 can be further simplified as $T_p = 2H/D$ and $K_p = 1/D$, which are the power system constant and the power system gain, respectively. Then, we can derive the following equation:

$$\{[\Delta P_r(s) - \frac{1}{R}\Delta f(s)]\frac{K_g}{1+sT_g}\frac{K_t}{1+sT_t} - \Delta P_d(s)\}\frac{K_p}{1+sT_p} = \Delta f(s). \quad (1)$$

In the above equation, the values of the time constants of T_g and T_t are much smaller than that of T_p, which is assumed to be zero. Meanwhile, because the turbine gain of K_t and the power system gain of K_p are fixed, adjustment of the value of K_g so as to satisfy $K_gK_t \approx 1$ for simplicity can be achieved (Elgerd, 1982).

Now, let us consider a simple situation in which the reference power increment has a fixed setting (i.e., $\Delta P_r(s) = 0$) and the load demand varies with a step change (i.e., $\Delta P_d(s) = \Delta P_d/s$); then, Eq. (1) can be reduced to

$$[-\frac{1}{R}\Delta f(s) - \Delta P_d(s)]\frac{K_p}{1+sT_p} = \Delta f(s). \quad (2)$$

Rearranging Eq. (2) gives

$$\Delta f(s) = \frac{-\Delta P_d}{s(2Hs+\beta)}. \quad (3)$$

By taking the inverse Laplace transformation of Eq. (3), the system frequency deviation can be obtained:

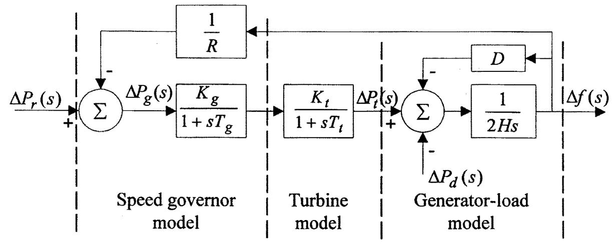

Fig. 1. Block diagram of the load frequency control model.

$$\Delta f(t) = -\frac{\Delta P_d}{\beta}(1 - e^{-t/\tau}). \quad (4)$$

Here, $\beta = D + 1/R$ represents the system frequency response characteristics, which can be deemed the percent change in load plus the percent change in generator output due to the per percent change in frequency (Prasetijo *et al.*, 1994). The value of β may vary according to the load type, governor performance and speed regulation setting. Its value typically lies within 10% ~ 20%/Hz of an interconnected power system. For an isolated power system, the value of β is smaller. The larger the value of β, the slower the frequency decline for a given amount of overload. In Eq. (4), τ is a time constant, $\tau = 2H/\beta$. In this paper, we choose the sign for ΔP_d such that $\Delta P_d > 0$ for a sudden increase in load and $\Delta P_d < 0$ for a sudden increase in generation.

When the values of β, H and ΔP_d are known, by using Eq. (4), the frequency variation curve can be plotted. However, the amount of disturbance of ΔP_d is often difficult to evaluate when a disturbance happens. Therefore, the initial slope of the frequency variation should be detected, as this is the only clue that can be used to calculate the amount of disturbance. The following equation, thus, must be formulated:

$$m_0 = \left.\frac{d\Delta f(t)}{dt}\right|_{t=0} = -\frac{\Delta P_d}{2H}. \quad (5)$$

Equation (5) means that if the initial rate of change of frequency is ascertained, the amount of disturbance can be calculated (i.e., $\Delta P_d = -2Hm_0$). Then, by applying the final-value theorem to Eq. (4), the frequency drop in the steady state can be readily computed as follows:

$$\Delta f_0 = \lim_{t\to\infty}[\Delta f(t)] = -\frac{\Delta P_d}{\beta}. \quad (6)$$

III. Load-Shedding Scheme Design

The load-shedding scheme can be seen as a tradeoff between maximum system protection and minimal service interruption. The proposed load-shedding scheme is described in this section.

1. Design Procedure

The first step in load shedding is to obtain the system parameters, including the inertia constant (H) and system stiffness (β). In general, experienced engineers can supply these parameters. This is followed by selection of the first shedding frequency (f_1) and minimum allowable operation frequency (f_{min}). Several utilities set their first shedding frequency at 59.5 Hz for a power system with a nominal frequency of 60 Hz (Smaha *et al*., 1980). When setting this shedding frequency, several factors should be prudently considered. Firstly, the first shedding frequency should not be too close to the nominal frequency. In this way, tripping on severe but non-emergency frequency swings can be avoided. Secondly, as larger turbine-generators in the system are not clearly rated for continuous operation below 59.5 Hz, setting the initial load shedding frequency at a relatively high value, such as 59.5 Hz, will limit the maximum frequency deviation. Thirdly, a load-shedding scheme starting at 59.5 Hz will be more effective in minimizing the depth of the under-frequency response for a heavy overload than will a similar scheme that has a lower first shedding frequency. In this stage, the selection of the minimum allowable frequency is even more important. If the system frequency is lower than the minimum allowable operating frequency, it may cause the system to collapse. Based on the operation record, a value of 57.0 Hz given for the minimum allowable frequency has been deemed to be reasonable for an isolated power system (Anderson and Mirheydar, 1992).

The next task is to determine the number of steps (N) and the range of the time interval (Δt). Over- or under-shedding might happen with a small disturbance for a large step size, while coordination problems might occur when an inappropriate number of shedding steps is adopted. Experience has shown that three to five steps are adequate for the load shedding task (Jones and Kirkland, 1988). As for determination of the range of the time interval, it can be judged based on the system characteristics the and types of under-frequency relays, all of which are not necessary the same at each shedding step. By incorporating this time delay, the impacts caused by system surges can be reduced. Nevertheless, unnecessary trips of generator protective relays may take place, thereby leading to a decline in the system frequency. To deal with this problem, a time-oriented procedure is proposed in this paper, where the load is shed at each pre-determined time interval. When the length of each time step is known, the coordination problem can be solved.

The following task is to determine the total amount of load to be shed (P_{LS}) and the amount of load to be shed at each step ($\Delta P_{LS,i}$). Upon encountering a disturbance, once the frequency variation curve is known, the initial rate of change of the frequency m_0 can be calculated. By substituting m_0 into Eq. (5), the amount of overload can be calculated based on $\Delta P_d = -2Hm_0$. Then, the amount of P_{LS} can be computed as follows:

$$P_{LS} = -2Hm_0 - (-2Hm_{0,min}) = -2H(m_0 - m_{0,min}), \quad \textbf{(7)}$$

where $-2Hm_{0,min}$ is the maximum allowable amount of overload in a system, $m_{0,min}$ is the slope at the minimum allowance operation frequency f_{min}, and $m_0 - m_{0,min}$ is the maximum allowable slope difference in frequency. Now, since the total amount of load to be shed is known, the amount of load to be shed at each step ($\Delta P_{LS,i}$) can be obtained by dividing total load by the number of shedding steps. It is also note worthy that for an isolated system, the fewer the steps, and larger the load to be shed per step compared with an interconnected system.

Using the information about the system parameters (H and β), load shed per step ($\Delta P_{LS,i}$), overload (ΔP_d) and time interval (Δt_i), the load frequency curve can be readily plotted with the aid of Eq. (4). The minimum operation frequency can, thus, be evaluated. If the minimum operation frequency is higher than the minimum allowable value of f_{min}, the load-shedding task is considered to have been accomplished, and the system reaches a new steady state. Otherwise, an additional modification process may be necessary to improve performance.

2. Modification

A modification task is required when the minimum operation frequency is lower than the minimum allowable operation frequency f_{min}. In such a scenario, based on the expression of Eq. (7), the total amount of load to be shed is deemed to be insufficient to maintain the frequency profile. To justify the required amount of load to be shed, the shedding frequency f_i at each step should be correctly determined. The frequency at the last step is denoted as f_L. For each step, the shedding frequency can be iteratively computed by using the following equations:

$$\Delta P_{d,1} = \Delta P_d - \Delta P_{LS,1}, \quad \textbf{(8)}$$

$$\Delta P_{d,i+1} = \Delta P_{d,i} - \Delta P_{LS,i+1},\ i = 1, 2, 3, ..., N-1, \quad \textbf{(9)}$$

$$f_{i+1} = f_i(1+\Delta f_i(\Delta t_i)),\ i = 1, 2, 3, ..., N-1, \quad \textbf{(10)}$$

where ΔP_d is the initial amount of overload, $\Delta P_{d,i}$ is the amount of overload after the i-th step, $\Delta P_{LS,i}$ is the amount of load shed at the i-th step, $\Delta f_i(\Delta t_i)$ is the frequency variation after i steps of time intervals Δt_i, and f_i is the frequency at the i-th step.

When the frequency at the last step is known, the maximum allowable change of frequency at the last step can be immediately calculated as, $\Delta f_{max} = f_{min} - f_L$ in Hz. The maximum allowable amount of overload becomes:

Table 1. Amount of Load Shed at Each Step (Scheme-1)

Number of steps (N)	Amount of load shed at each step ($\Delta P_{LS,i}$) (p.u.)				
	1	2	3	4	5
3	0.2667	0.2667	0.2666		
4	0.2000	0.2000	0.2000	0.2000	
5	0.1600	0.1600	0.1600	0.1600	0.1600

Table 2. Amount of Load Shed at Each Step (Scheme-2)

Number of steps (N)	Amount of load shed at each step ($\Delta P_{LS,i}$) (p.u.)				
	1	2	3	4	5
3	0.4571	0.2286	0.1143		
4	0.4267	0.2133	0.1067	0.0533	
5	0.4129	0.2065	0.1032	0.0516	0.0258

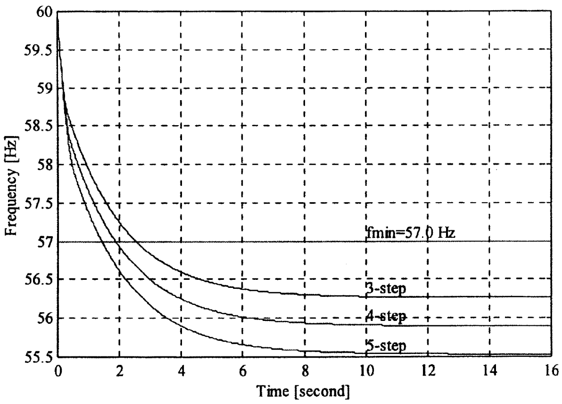

Fig. 2. Load frequency curve of Scheme-1.

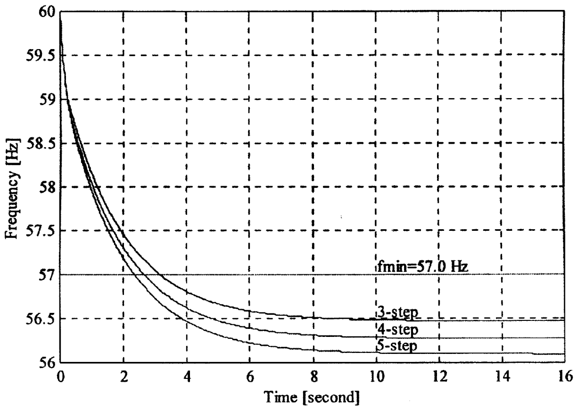

Fig. 3. Load frequency curve of Scheme-2.

$$\Delta P_{max} = \beta(f_L - f_{min}). \quad \textbf{(11)}$$

The required amount of load to be shed is, therefore, modified as follows:

$$P'_{LS} = -2Hm_0 + \beta(f_{min} - f_L), \quad \textbf{(12)}$$

where P'_{LS} represents the new amount of load to be shed after the modification is made and ΔP_{max} is the maximum allowable overload after the last step. With this new amount of load to be shed, rapid decline in system frequency can be avoided.

IV. Numerical Simulations

Numerical simulations have been performed to verify the effectiveness of the proposed algorithm. For an isolated system, the worst scenario for a shedding schedule may include all loads. Therefore, the maximum disturbance at 100% of the generation (ΔP_d = 1.0 p.u.) was considered in this test. As a test example, for an isolated power system with H = 4.5 seconds and β = 8%/Hz, if the first shedding frequency f_1 is selected as 59.5 Hz and the minimum allowable operation frequency f_{min} is 57.0 Hz, then the initial rate of change of frequency of m_0 can be obtained using Eq. (5), $m_0 = -0.1111$ p.u./s.

1. Test Case 1

In this test case, a value of –0.1111 p.u./s for m_0 was assumed to be detected from the frequency variation curve, and the overload became 1.0 p.u. (= $-2 \times 4.5 \times (-0.1111)$). By means of Eq. (7), a load of 0.8 p.u. to be shed was computed. For this test case, Tables 1 and 2 list the amounts of load to be shed at each step when 3, 4 or 5 steps was selected as the number of shedding steps. The loads shown in Table 1 were shed equally at each step, which is called Scheme-1 in this paper, while the loads shown in Table 2 were shed in the geometry mean manner, where the load shed at a given step is half the load shed at the preceding step. This type of shedding scheme is called Scheme-2. Both schemes have a time interval of Δt = 0.1 sec. in their shedding procedure.

Figure 2 and Fig. 3 depict load frequency curves for Scheme-1 and Scheme-2, respectively. From these figures, the minimum frequencies of both schemes are found to be lower than f_{min} = 57.0 Hz. The load shedding task was not successfully accomplished.

To improve performance, the modification process mentioned in Section III.2 was adopted. Based on this modification process, the shedding frequency at the last step, f_L, was first calculated. Using Eqs. (8) – (10), we could obtain f_L values of 58.7270, 58.3455 and 57.9666 Hz for 3 shedding steps, 4 shedding steps and 5 shedding steps for Scheme-1, respectively. Meanwhile, 58.9464, 58.7363 and 58.5555 Hz were the values of f_L obtained for 3 shedding steps, 4 shedding steps and 5 shedding steps for Scheme-2, respectively.

With the above results for f_L, the amount of load to be shed could be modified using Eq. (12). For Scheme-1, when 3, 4 or 5 were assigned for the number of shedding steps, the

Table 3. Amount of Load Shed at Each Step (Scheme-3)

Number of steps (N)	Amount of load shed at each step ($\Delta P_{LS,i}$) (p.u.)				
	1	2	3	4	5
3	0.2873	0.2873	0.2872		
4	0.2231	0.2231	0.2231	0.2231	
5	0.1846	0.1846	0.1845	0.1845	0.1845

Table 4. Amount of Load Shed at Each Step (Scheme-4)

Number of steps (N)	Amount of load shed at each step ($\Delta P_{LS,i}$) (p.u.)				
	1	2	3	4	5
3	0.4825	0.2412	0.1206		
4	0.4593	0.2296	0.1148	0.0574	
5	0.4519	0.2260	0.1130	0.0565	0.0282

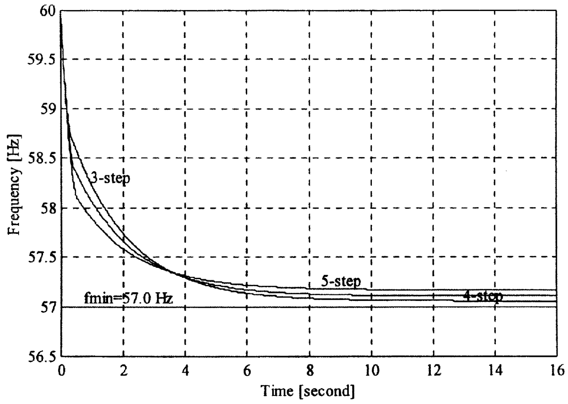

Fig. 4. Load frequency curve of Scheme-3.

corresponding modified total amount of load (P'_{LS}) to be shed became 0.8618, 0.8924 or 0.9227 p.u., respectively, while for Scheme-2, the corresponding amount of load to be shed became 0.8443, 0.8611 or 0.8756 p.u., respectively. In the paper, Scheme-3 is the name for the modified Scheme-1, while Scheme-4 is the name for the modified Scheme-2. Table 3 and Table 4 list the amounts of load shed at each step using Scheme-3 and Scheme-4, respectively. For these new shedding schemes, Fig. 4 and Fig. 5 plot the corresponding load frequency curves.

As observed in Fig. 4, all the minimum operation frequencies were higher than 57.0 Hz. They were found to be 57.0778 Hz for 3 shedding steps, 57.1263 Hz for 4 shedding steps and 57.1877 Hz for 5 shedding steps. Consequently, Scheme-3 is deemed an effective load-shedding scheme. As seen from the plot shown in Fig. 5, all the minimum operation frequencies were also higher than 57.0 Hz when different numbers of shedding steps were employed. These results reveal that Scheme-4 is also a feasible load shedding strategy.

Table 5. Frequency Settings Given at Each Step

Number of steps (N)	Frequency setting at each step (Hz)				
	1	2	3	4	5
3	59.5	59.3	58.9		
4	59.5	59.3	59.0	58.6	
5	59.5	59.3	59.0	58.7	58.3

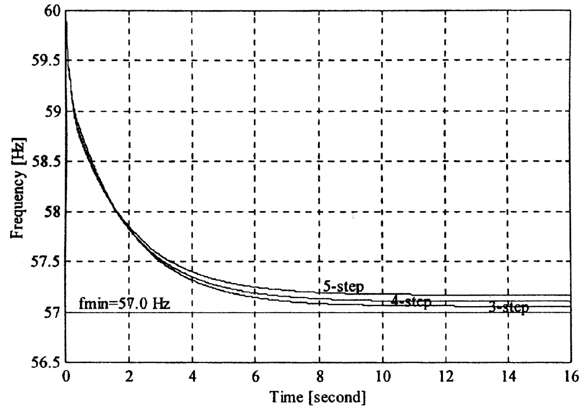

Fig. 5. Load frequency curve of Scheme-4.

For the test case, these plots help confirm the feasibility of the method.

2. Test Case 2

The proposed modification method is also effective in a frequency setting strategy for load shedding. Once the first shedding frequency is selected, the remaining shedding frequency intervals can immediately be chosen. Theoretically, a frequency interval of 0.2 Hz works better in the upper shedding frequencies, while 0.3 Hz or 0.4 Hz intervals work better in the lower ones and help reduce the amount of over-shedding (Smaha *et al.*, 1980). For this test case, we chose 0.2 Hz as the first frequency interval, 0.4 Hz as the last one and 0.3 Hz as the remaining frequency interval. Therefore, the proposed modification method was employed for Scheme-2 (Scheme-1 could be treated in the same way as Scheme-2) using the frequency setting strategy. Table 5 lists the frequency setting given at each step. Figure 6 plots the corresponding load frequency curves. As observed from the plot shown in Fig. 6, all of the curves are lower than 57.0 Hz, so the modification process was needed.

Table 6 list the results obtained using the proposed modification procedure described in Section III.2 for the amount of load shed at each step when the modified frequency setting strategy was performed. Figure 7 plots the corresponding load frequency curves. As the plot depicts, although the computed results represented by different curves for the number of shedding steps overlap, all the frequencies were higher

Table 6. Amount of Load Shed at Each Step When the Modified Frequency Setting Strategy Is Employed

Number of steps (N)	Amount of load shed at each step ($\Delta P_{LS,i}$) (p.u.)				
	1	2	3	4	5
3	0.4891	0.2446	0.1223		
4	0.4651	0.2325	0.1163	0.0581	
5	0.4542	0.2271	0.1135	0.0568	0.0284

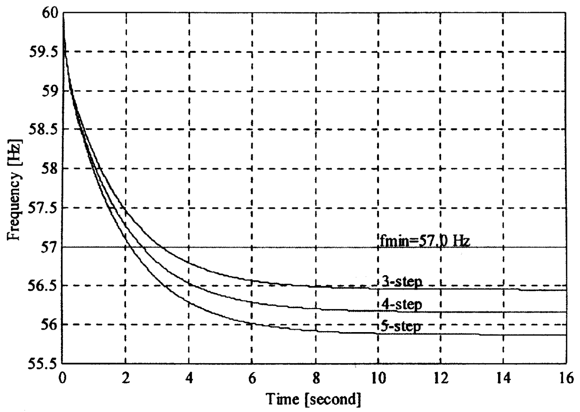

Fig. 6. Load frequency curve when the frequency setting strategy is employed to perform load shedding.

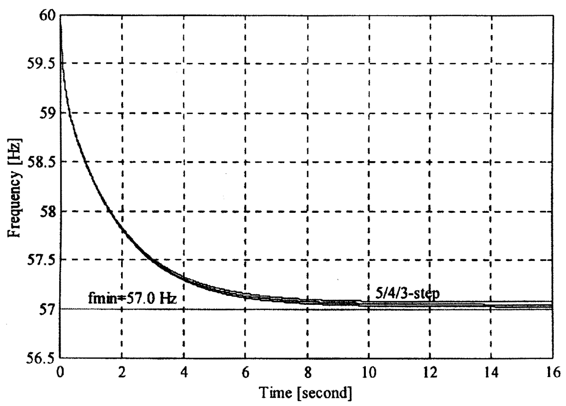

Fig. 7. Load frequency curve when the frequency setting strategy is modified and employed to perform load shedding.

than the minimum allowable frequency of 57.0 Hz.

V. Conclusions

A time-oriented approach to designing a load-shedding scheme has been proposed in this paper. To facilitate computation, a modification algorithm that considers the maximum frequency change at the last shedding step is embedded into the shedding scheme. The proposed method overcomes the coordination problem and helps determine the appropriate amount of load to be shed. Without predicting the amount of system overload, the method has also been proved to be effective in avoiding the problem of over- or under-shedding. By means of case studies with numerical simulations, the proposed method has been shown to have the advantages of simplicity, flexibility, and efficiency for dealing with load shedding problems.

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電力系統時間導向法之卸載設計

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摘　要

本文提出一時間導向法來設計電力系統的卸載策略，此方法可克服低頻電驛協調困難的問題，同時，爲了減低由於系統動態導致卸載失敗的可能性，亦提出一修正方法改善之，此修正方法以最後一段卸載後系統所能再允許的頻率最大變化量爲基礎，除了可更準確的計算出系統所需的總卸載量外，更可有效的抑制系統頻率的下降，經過數值模擬的結果，證實本文所提的方法的確具有實用性。