

AN INTELLIGENT ADAPTIVE LOAD SHEDDING SCHEME

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Abstract – This paper provides a self-healing strategy to deal with catastrophic events when the system vulnerability analysis indicates that the system is approaching an extreme emergency state. In our approach, the system is divided into smaller islands with consideration of quick restoration. Then an intelligent adaptive load-shedding scheme based on the rate of frequency decline is applied. The proposed scheme is tested on a 179 buses 20 generators sample system and shows very good performance. Due to the uncertainties in power systems, the load-shedding scheme needs to adjust its decision criteria in an autonomous manner. A Reinforcement Learning (RL) technique is discussed and a dynamic simulation with the intelligent load shedding control scheme is described to validate the RL technique.

Keywords: *islanding, load shedding, self-healing, Reinforcement Learning*

1 INTRODUCTION

Power systems are being operated closer to the stability limit nowadays as deregulation introduces many more economic objectives for operation. As the system becomes more interconnected, weak connections, unexpected events, hidden failures in protection systems, human errors and other reasons may cause the system to lose balance and even leads to catastrophic failures. Iowa State University, University of Washington, Virginia Polytechnic Institute and State University, and Arizona State University have worked as a consortium to conduct research on power system network security issues. The project is being conducted under a contract from the Electric Power Research Institute (EPRI) and the U. S. Department of Defense (DoD). One of the tasks involves the development of self-healing schemes for power systems, which relates directly to recent events in power-starved California. Our work is dedicated to designing the self-healing strategy to handle the long-term frequency instability emergency. When a power system is subjected to large disturbances, and the vulnerability analysis indicates that the system is approaching a catastrophic failure, control actions need to be taken to limit the extent of the disturbance. In our approach, the system can be separated into smaller islands at a slightly reduced capacity, but with the added advantage that the system can be restored quickly. Then by exploring a carefully designed load-shedding scheme based on the rate of frequency decline, we limit the extent of the damage, and are able to restore the system rapidly. We refer

to this corrective control scheme as controlled islanding followed by adaptive load shedding based on the rate of frequency decline.

Since power systems are dynamic and difficult to model in advance, control schemes should be capable of adjusting their decision criteria / parameters adaptively and autonomously. In this paper, the reinforcement learning method is introduced to provide suitable basis for the adaptation. The temporal difference learning method has been implemented for the self-healing schemes (i.e., load shedding scheme) to provide the reinforcement function.

Subsumption architecture [1], which is used in the field of controlled robots, is adopted here to identify the hierarchies of the various controls, protection, and communication systems between various agents in the deregulated electric utility environment. The architecture is based on the premise that storing models of the world is dangerous in dynamic and unpredictable environments because representations may be incorrect or outdated. It defines layers of Finite State Machines (FSMs) that are augmented with timers. Sensors feed information into FSMs at all levels. The FSMs of the lowest level are control actuators. The FSMs of the higher levels may inhibit (attenuate the signal of one output wire) or suppress (attenuate the signal on all output wires) output values of the FSMs on the layers below them. In this manner, a hierarchy of progressively refining behaviors may be established. Agents designed using the Subsumption architecture do not use symbol manipulation in a fixed manner to represent processing. They also have no global knowledge and are generally decentralized. The agents are non-programmable, single-purpose devices because of their lack of symbolism and global knowledge. However, they have the advantage of rapid response for dealing with dynamic and unpredictable events. A load-shedding scheme based on the subsumption model is designed with consideration of certain criteria. The proposed scheme is tested on a 179 buses 20 generators sample system and shows very good performance.

2 CONTROLLED ISLANDING

In this step, we employed a two-time-scale method to determine the groups of the generators with slow coherency. This method considers the structural characteristics of the power system to determine the interactions of the various generators and find the strong and weak couplings. The theory is implemented by running the Dynamic Reduction Program 5.0 (DYNRED) software

obtained from the EPRI software center. Through the selection of the two-time-scale option, the coherent groups of generators can be obtained on any power system. We also develop an automatic islanding program to fully support the application of theory. The program is dedicated to searching for the optimum cut sets with consideration of certain boundary criteria after we have the grouping information.

3 LOAD SHEDDING SCHEME

3.1 General

Controlled islanding divides the power system into islands. Some of these islands are load rich and others may be generation rich. Generally, in a load rich island, the situation is more severe. The system frequency will drop because of the generation shortage. If the frequency falls below a certain set point, e.g., 57.5Hz, the generation protection system will begin operation and trip the generator, further reducing the generation in the island and making the system frequency decline even more. In the worst case, the entire island will blackout. In a load deficient island, either intentional or forced generator tripping will reduce the gap between the generation and the load. As a result, we put more effort to save the load rich island and develop a two-layer load-shedding scheme to perform the task [2].

3.2 The New Load Shedding Scheme Under Subsumption Model

In the literature, there exist two kinds of load shedding schemes: load shedding based on frequency decline and load shedding based on frequency declining rate [3][4]. The first approach has mostly conservative settings because of the lack of the information regarding the magnitude of the disturbance. Although this approach is effective in preventing inadvertent load shedding in response to small disturbances with relatively longer time delay and lower frequency threshold, they are not able to distinguish between the normal oscillations of the power system and the large disturbances on the power system. Thus, they are prone to shedding fewer loads. This is not beneficial to the quick recovery of the island and may lead to further cascading events. As a result, we develop a load shedding scheme based on the rate of frequency decline, which can identify the magnitude of the disturbance. At the same time, we incorporate the conventional load-shedding scheme into our Subsumption model as to form a new two-level load shedding scheme shown in Figure 1.

Normally the relay will run under the conventional load shedding scheme. The conventional load shedding scheme has longer time delays and lower frequency thresholds, which can be used to prevent inadvertent load shedding in response to small disturbances. If the system disturbance is large and exceeds the signal threshold, the second layer will be activated and send an inhibition signal to the first layer and the load shedding

scheme based on the rate of frequency decline will take effect. This layer of the load shedding scheme will shed more loads quickly at the early steps to prevent the cascading events in the island. This can greatly enhance the system's ability to withstand large disturbances. In all, the new two-level load shedding scheme has the following explicit features:

- Combines the advantages of load shedding schemes based on frequency and rate of frequency decline and makes the scheme suitable for both normal and extreme contingencies.
- It's suitable to be used for recovery following the islanding after a large disturbance. When combined with islanding, the possible size of the disturbance and its effect to the island will be calculated in the form of the initial frequency decline rate. The rate will in turn act as a threshold to compare with the local measurement of the rate of frequency decline and determine which level of the scheme is to be used. Thus it ensures a local implementation if the threshold is preset. Or, with a central signal of the threshold, the scheme can be implemented for wide area coordinated load shedding

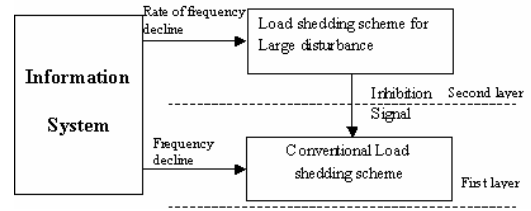


Figure 1: The Subsumption model for the load shedding scheme.

3.3 Determine the Magnitude of the Disturbance

A variable that measures the magnitude of disturbance should be determined in order to make the subsumption approach feasible. From an intuitive analysis of [5], the rate of frequency decline at the beginning of the disturbance can accurately reflect the amount of the disturbance. From chapter 3 of [6], we have

$$\frac{df_i}{dt} = -\frac{60 \times P_{sik}}{2H_i} (P_{L\Delta}(0^+) / \sum_{j=1}^n P_{sik}) \quad i=1,2,\dots,n \quad (1)$$

In (1), we sum up all the equations to obtain

$$\frac{d\bar{f}}{dt} = -60 \times P_{L\Delta} / \sum_{i=1}^n 2H_i \quad (2)$$

where

f_i is the frequency of generator i in Hz.

$\frac{d\bar{f}}{dt}$ is the average rate of frequency decline in

Hz/Second

$$\bar{f} = \frac{1}{2p} \times (1 / \sum_{i=1}^n H_i) \sum_{i=1}^n w_i H_i \quad (3)$$

P_{sik} is the synchronizing power coefficient between generator i and the disturbance place k , in pu.

$P_{L\Delta}$ is the magnitude of the disturbance, in pu

H_i is the inertia of each generator, in pu

ω_i is the rotor speed of generator i , in pu.

We define

$$m_i = \frac{df_i}{dt} \quad (4)$$

$$m_0 = \frac{d\bar{f}}{dt} \quad (5)$$

Substituting (5) into (2), we have:

$$m_0 = -60 \times P_{L\Delta} / \sum_{i=1}^n 2H_i \quad (6)$$

The equation can be alternatively be written as

$$P_{L\Delta} = -m_0 \times \sum_{i=1}^n 2H_i / 60 \quad (7)$$

Since H_i is constant, the magnitude of the disturbance can be directly related to the average rate of system frequency decline. Hence, m_0 can be an indicator of the severity of the disturbance. The rate of frequency decline at the beginning of the disturbance can be used as the input signal of the second layer. Once the threshold of $P_{L\Delta}$ to activate the second layer is decided, the corresponding m_0 can be calculated. When the disturbance occurs, we measure m_i at each bus and compare it with m_0 . If $m_i > m_0$, the second layer is activated; otherwise the conventional load shedding scheme is used.

By using m_i at each bus to determine the amount of load that should be shed locally, the system oscillations after the disturbance can be reduced. We know that at the beginning of the disturbance, the impact of disturbance is shared immediately by the generators according to their synchronizing power coefficients with respect to the bus at which the disturbance occurs [6]. Thus, the machines electrically close to the point of impact will pick up the greater share of the load regardless of their size. Although the disturbance is ultimately shared according to the inertia of each machine, sometimes the frequency of some generators near the disturbance can drop below 57 Hz before reaching the final state. By using the value at each bus, the buses whose frequencies drop quickly are likely to have more loads shed locally; this can reduce the frequency difference and system oscillations.

3.4 Determine the Threshold $P_{s\Delta}$.

Considering the governor protection system limitation and regional operation criteria, we define $P_{s\Delta}$ as the minimum load deficit that can drive the system average frequency below 57 Hz. This frequency threshold is chosen because it is widely recognized that the system can't operate below 57 Hz.

There are three main reasons why the system can't operate below 57 Hz.

- Coordination with the governor-turbine system. Under-frequency operating limitations imposed by manufactures of turbine-generator units are primarily concerned with the avoidance of resonant frequencies and turbine blade fatigue. Since fatigue effects are cumulative, the limitation is defined in terms of total accumulated times of operation within specified frequency ranges. Turbine manufacturers provide limitations of various turbines to frequency variation. Based on this data it is reasonable to choose 57 Hz as system operation limit [5].
- Coordination with the plant auxiliary system. Nuclear units having a pressurized water reactor steam supply use special under-frequency protection for their primary system reactor coolant pumps. For these units, this protection will trip the coolant pumps and shutdown the reactor at the fixed time of 0.25s and a pickup setting of 57.0 Hz [7].
- Coordinate with existing operation criteria. According to the North East Power Coordinating Council (NPCC) criteria, the generation rejection should be deployed immediately if system frequency drops below 57 Hz [8].

To find the $P_{L\Delta}$, we use a reduced model for reheat unit for frequency disturbance shown as in Figure 2 [4].

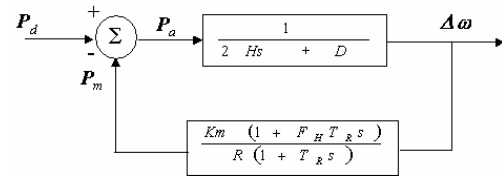


Figure 2: The reduced model of reheat unit for frequency disturbance

Here

K_m is mechanical power gain factor

H is inertia constant, seconds

F_H is high pressure power fraction

D is damping factor

T_R is reheat time constant, seconds

R is fraction of the reheat turbine

P_d is disturbance power

Using this reduced model and normalize, we can obtain that when $P_{L\Delta} = 0.3 P_{sys}$, the lowest system average frequency for this disturbance is 57 Hz. So we choose $0.3 P_{sys}$ as the threshold value of $P_{L\Delta}$ for the new load-shedding scheme.

3.5 Frequency Threshold, Step Size and Time Delay.

The frequency threshold should be chosen carefully. First, it should not be too close to normal frequency in order to avoid tripping on severe but non-emergency frequency swings. On the other hand, it is more effective to shed load earlier.

The step size is an important variable in load shedding. Conventionally, the amount of load shed at each step is increased while the system frequency decreases. This choice is reasonable for those schemes that use the frequency as the criterion to shed load because before the system deteriorates, it is unreasonable to shed too much load if the disturbance is unknown. It has also been observed that for large disturbances, such schemes may be insufficient to arrest system frequency decline. Our second layer of load shedding scheme, as stated before, will only take action when the disturbances are large enough to cause the system frequency to drop below 57 Hz. So instead of increasing the step size while system frequency is decreasing, we set the first step to be the largest step size. Since the first layer of the new load shedding scheme will mainly deal with small disturbances, we use the conventional philosophy.

For the steps of load shedding, three facts are observed [9]:

- Frequency steps must be far enough apart to avoid overlap of shedding due to (intentional or inherent) time delay.
- The number of steps doesn't have very great impact on the effect of load shedding.
- Generally, the threshold of the last step of load shedding is chosen no less than 58.3Hz.

Time delay is very important for load shedding schemes to avoid over-lapping and unexpected action for small frequency oscillations. Generally, for the conventional load shedding scheme, the delay time for the first step is usually long to avoid unexpected action due to small frequency oscillations. For the following steps, the more the frequency declines, the quicker is the action. For the second layer of the new scheme, to prevent sharp frequency declines following a large disturbance, we set the delay time for the first step of the second layer as 0 cycles.

Finally, the two layers of load shedding scheme can be shown in the Table 1.

	59.5Hz	59.3Hz	58.8Hz	58.6Hz	58.3Hz
$m_i > m_0$	20% (0C)		5% (6C)	4% (12C)	4% (18C)
$m_i < m_0$		10% (28C)	15% (18C)		

Table 1: Step size and delay time of the two layers as percentage of the total load.

4 SIMULATION RESULT

The self-healing scheme is tested on a 179-Bus, 29-Generator sample system. The DYNRED program in the PSAPAC package was chosen to form four groups of generators based on slow coherency. With the help of the automatic islanding program, we determine the cut

sets of the island with consideration of the least generation-load imbalance and topology requirements.

To test the system response to a severe contingency, the following three lines in the system are tripped simultaneously. This corresponds to a catastrophic transmission failure where an incident takes out all the three transmission lines simultaneously. These lines are connected between buses:

- Bus 83 - Bus 168, Bus 83 - Bus 170, and Bus 83 - Bus 172

Simulations conducted on the system indicate that this disturbance will result in the system being unstable. To save the system from an impending blackout, we split the system into three islands 0.2 seconds after the contingency. In order to create the islands, the following lines are tripped:

- Bus 133-Bus 108, Bus 134-Bus 104, and Bus 29-Bus 14

After islanding, the system is divided into three areas. These areas are shown in Figure 3.

The three islands can be characterized as the northeast island, the central island and the south island. The south island and the central island are load rich area. The other island is the generation rich area. The central island has 5118.0MW generation and 7005.9MW load. Under-frequency load shedding with proposed scheme is performed in the central island to maintain acceptable frequency.

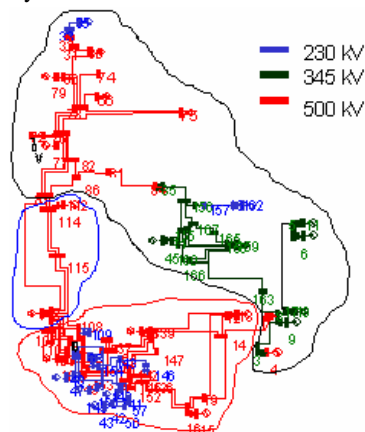


Figure 3: Three islands of 179-buses system

Simulations are conducted using EPRI's Extended Transient-Midterm Stability Package (ETMSP).

The simulation shows that, following the disturbance, the system will lose stability without any self-healing strategy. In the central island, 1810MW active load is shed under the conventional load shedding scheme while 1450MW active load is shed under the new load shedding scheme. In the same situation, the load-shedding scheme based on the rate of frequency decline sheds fewer loads than the conventional load-shedding scheme. At the same time, the frequency responses of the system are more stable under the new scheme than

they are under the conventional scheme. Figure 4 shows a typical generator's frequency response in four situations.

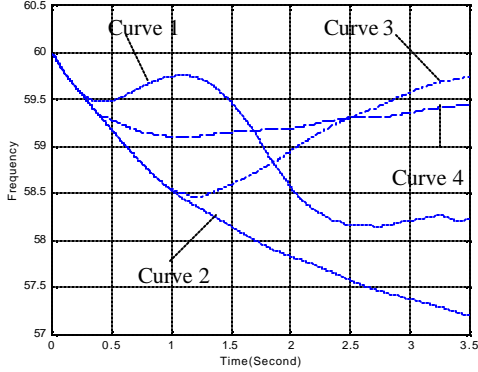


Figure 4: Frequency response of Generator 118 after the contingency of the 179-bus system. Curve 1: Without self-healing. Curve 2: Islanding with no load shedding. Curve 3: Islanding followed by load shedding based on frequency difference. Curve 4: Islanding followed by load shedding based on rate of frequency decline.

5 ADAPTIVE LOAD SHEDDING CONTROL

An important class of methods for the software modules to adapt and learn is the supervised learning in which training data is provided to an agent by a supervisor within limited training time. In this case, the software module is passively guided through the task, but it is often difficult for the supervisor to generate representative scenarios [10]. Another applicable method, unsupervised / autonomous learning, arises when the software module attempts to learn a task without the passive guidance from a supervisor. In such situations, the software module has to solve the task by executing trial-and-error actions, exploring the state and space and collecting its own training data.

To realize the autonomous and adaptive learning capability, the reinforcement learning technique has been applied to the load shedding scheme. Reinforcement learning is learning by interaction with a real environment. Reinforcement learning is based on the common sense that if an action is followed by a satisfactory state of affairs, or by an improvement in the state of affairs, then the tendency to produce the actions is strengthened (i.e., reinforced) [11]. The reinforcement learning method does not need to have both an exact model of the environment and a supervisor because the method learns autonomously through the interactions with the power systems.

The temporal difference (TD) method can be used for the software modules, which perform self-healing control actions, to provide the reinforcement function [12]. The TD method can be represented by the formula as follows: $V_{n+1} = V_n + a(R_n - V_n)$, where n is the index of the current learning-step, R_n is the cumulative actual reward

value received from the environment (i.e., the summation or average of actual reward values from the current state to the terminal state in one sequence of actions), a ($0 \leq a \leq 1$) is a constant step-size parameter which is called the *learning factor*, V is the function estimation value that indicates the efficiency of an action taken by the control scheme in the current state. For example, at each time step n , the load shedding control scheme takes a load shedding control action, and one step later the module receives the scalar reward value R_n to update V of the action taken by the module, which indicates the efficiency of the load shedding control action to improve system stability. The load shedding control action that has the maximum (or minimum) value of V is the optimal action, which is also called a *greedy action*. For the adaptive load shedding control scheme, the TD method is used to find a sequence of optimal load shedding control actions. The purpose of the load shedding control is to keep the system stable. Thus the reward value R in the TD method is a normalized value of system frequency, i.e.,

$$r = f/60 \text{ (if } f \leq 60) \text{ or } |f - 60|/60 \text{ (if } f > 60) \quad (8)$$

V is the accumulated reward values of R through a sequence of load shedding controls. The reward value R is a cumulative reward value for all states in one sequence of controls. If there are three states in a sequence of controls, R is the summation of r_1 , r_2 , and r_3 where r_1 , r_2 , and r_3 are the reward value at each state, respectively. Therefore the function estimation value V for the n^{th} learning iteration at the state 1 is:

$$V_{n+1} = V_n + a(r_1 + r_2 + r_3 - V_n) \quad (9)$$

In other words, the greedy load shedding action at a state has the maximum value of R so the greedy sequence of load shedding control actions is the collection of greedy load shedding controls at each state.

The TD method has been applied to the load shedding schemes for large disturbances, which uses the rate of frequency decline to decide the amount of load shedding. Based on Table 1, let us assume:

- State 1: the rate of frequency decline exceeds the threshold value (i.e., m_0) AND the frequency indicates 59.5 Hz,
- State 2: the rate of frequency decline exceeds the threshold value AND the frequency indicates 58.8 Hz,
- State 3: the rate of frequency decline exceeds the threshold value AND the frequency indicates 58.6 Hz, and
- Terminal state: the state in which the current state is not matched with any state of states 1, 2, and 3.
- The optimal amount of load shedding in the state 1 is 20%.

The disturbance scenario to show the adaptive capability of the load shedding scheme is shown in Section 4. The load shedding control actions based on Table 1 are taken to the Bus 119 and the frequency response at Bus 114 is measured and normalized between 0 and 1 to calculate the function estimation value (or the cumulative reward values). Figure 5 illustrates the trajectory of the function estimation value V for the state 1. Based on the assumptions described above, the maximum function estimation value V for the state 1 is 2.0.

Figure 5 illustrates the function estimation value converges to 2.0 which is the optimal function estimation value. In other words, the TD method is able to find the optimal control action (i.e., 20 % load shedding in the state 1) when the function estimation value V converges to 2.0. In Figure 5, the greedy action at point (1) is 11 % load shedding, the greedy action at point (2) is 14 %, and the greedy action at point (3) is 20 %. Figure 6 compares the frequency responses at Bus 114 with different load shedding amount, i.e., 11%, 14%, and 20%.

The frequency response with 20% load shedding becomes stable faster than the responses with the other two load shedding actions.

The convergence criteria has been developed for the load shedding control purposes in [12-13]. Based on the theory of convergence, the learning factor a has to be chosen between 0 and 0.65. For the simulation in this paper, 0.55 is chosen to assure the convergence of the learning process.

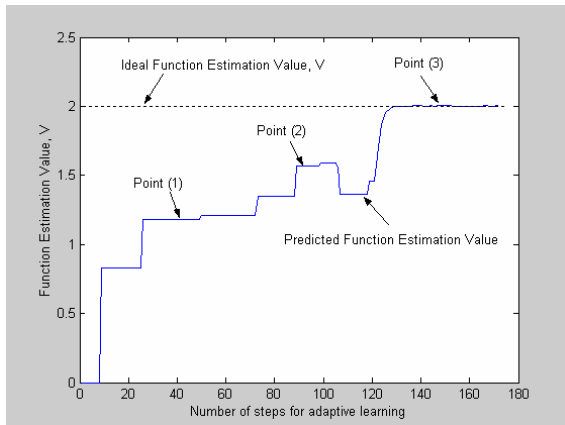


Figure 5: The function estimation value through the learning process.

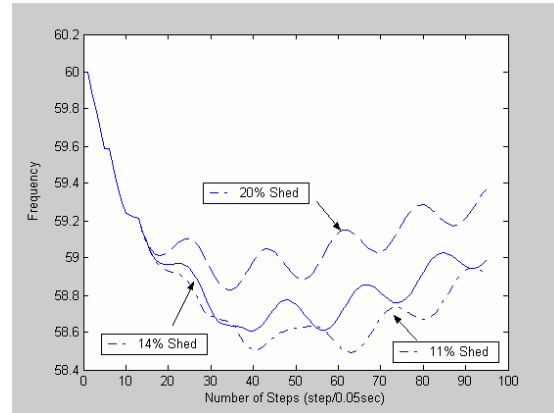


Figure 6: The frequency response at Bus 114 with different amount of load shedding.

6 CONCLUSION

In this paper, an adaptive load-shedding scheme to be used as a part of the corrective control for the large disturbance is explained in detail. The scheme is tested on the 179-buses sample system and shows very good performance. The new load-shedding scheme raises the stability performance of the system by shedding fewer loads comparing to the conventional load-shedding scheme. Due to the uncertainty of power systems, the software modules that perform self-healing control actions need to change their decision criteria or parameters adaptively and autonomously. The TD method is implemented and tested with the load-shedding scheme. The simulation result demonstrates how the software modules can learn adaptively in order to find an optimal control action(s) in dynamic and unpredictable power systems.

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