A Way to Evaluation the Process Immunity Time of Customers' Sensitive Industries Processes

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Abstract. The premise of voltage sag mitigation for sensitive industrial processes is to reasonably assess the economic losses caused by voltage sag. And the process immunity time is the key information in the process of economic loss assessment. Existing research usually obtains process immunity time through monitoring systems or overall testing. However, in the actual situation, due to various constraints, the traditional method of obtaining the process immunity time is inconvenient. To get PIT more conveniently, a sensitive process immunity evaluation method based on response information flow is proposed in this paper. This method regards sensitive industrial processes as a composite system. According to the function of each part of the system and the response characteristics of voltage sag, it can be divided into three modular combinations, which are delayed structure, competitive structure, and conductive structure. According to the delay time and module combination characteristics of module response to the voltage sag, the propagation path of response information flow caused by sag can be determined, and the process immunity time can be evaluated. Finally, a case study of the painting process of a car factory in southern China shows that the proposed method can be applied to the sensitive process immune time assessment.

1. Introduction

In recent years, the power quality problem has become the focus of industry and academia, in which the voltage sag problem has great impact and loss on users [1]. The influence of voltage sag on industrial process is usually manifested as the failure of sag sensitive equipment. Domestic and foreign scholars have carried out a lot of research on the voltage sag immunity time of typical sensitive devices such as AC contactor (ACC) [2], adjustable speed drive (ASD) [3], and formed equipment. The voltage tolerance curve (VTC) is the core of the more mature sag sensitive equipment voltage sag immune time evaluation system. However, independent research on a single device is not sufficient to characterize the sag immunity time of the entire process.

The concept of process immunity time (PIT) introduces process parameters as an indicator of immune strength [4], taking into account the user process state. Based on this concept, a variety of methods for estimating the voltage sag immunity time of the process were proposed, such as the [5-7], which improved the accuracy of the original evaluation system but did not elaborate on how to easily obtain the PIT. In actual research, it is often difficult to directly obtain user PIT due to factors such as technology or user willingness.
Therefore, in order to improve the convenience of obtaining PIT, this paper proposes a process immune time evaluation method based on response information flow based on the research results of existing typical sag sensitive equipment and the analysis of the actual industrial structure. A case study of a sensitive process in a car factory compares it with the results of a traditional holistic test study, illustrating the rationality of the proposed method.

2. Immunity time and response information flow

2.1. Immunity time

The process immune time is defined as the time from when the voltage is interrupted when the process parameters are out of limits (Fig. 1(a)) [4].

\[
\text{PIT} = t_2 - t_1
\]  

Where \( t_1 \) is the sag occurrence time, \( t_2 \) is the parameter overrun time, and \( \Delta T \) is the process parameter response dead time. The PIT concept relies on the characterization system and the sensitive devices therein, so it can be generally described as:

\[
\text{XIT}_K = [t_2 - t_1] \text{[IT]}_K
\]  

Equation (2) represents the immunity time (IT) of system X when module K fails, based on the physical parameter PX of system X. XITK can be decomposed into module immunization time \( \text{KIT} \) and module K failure time \( \text{XFT}K \) (Fig. 1(b)).

\[
\text{XIT}_K = \text{KIT}_K + \text{XFT}_K
\]  

It can be seen that determining the fault response time of an object only needs to know the fault triggering moment and the fault determining the moment. For module K, the fault triggering time is the sag occurrence time \( t_1 \), and the fault determination time is the module key parameter PK time limit time \( t_2 \). For the next link, the fault triggering time is \( t_2 \), and the fault determination time is the PX overrun time \( t_3 \). By analogy, the layer-by-layer modular analysis can be used to estimate the process response time.

![Figure 1. Concepts related to immunity time](image)

2.2. Response information flow

When a system is subject to external disturbances, different modules of the system will respond differently, and the changes of the physical parameters and the change of the operating state involved in each response are defined as the response information of the link.

The response information of different links can be characterized by the process parameters that can be monitored. The response information of each link is different in time and space. Generally, the trend of the external disturbance input point to the target output point is inevitable. The propagation trend of information is defined as the response information flow of the system, which reflects the response mechanism of the system when it is affected by voltage sag.

3. Voltage sag immunity time assessment

3.1. Module immunization time

As described in Section 2.1, the module immunization time can be quantified by the immunization time KIT. There are differences in KIT due to differences in voltage amplitude. Fully portraying the
module's immune time requires the use of a voltage-immunity time curve (V-ITC), as shown in Figure 2.

Figure 2. V-ITC schematic

The main difference between V-ITC and traditional voltage tolerance curves (VTC) is that it focuses on the time of equipment failure under the corresponding sag amplitude, while VTC is concerned with the corresponding sag amplitude and duration. The state of the device failure under the feature. Therefore, the V-ITC can be obtained by recording the expiration time of the device judgment condition/key parameter under the corresponding sag amplitude. It provides module immunization time information at different amplitudes.

3.2 Combination module response time

The module response time $\Delta t$ refers to the time difference between the module output change and the input change. For a single module, its response time $\Delta t$ is the module's immune time $KIT$. The $\Delta t$ of the same module also depends on the influence factor $IX$ of the output when the upper module fails. For the cooling tower system described in [4], the time during which the front module cooling water pump fails or the fan failure causes the process to fail is different. Depending on the functional differences of the modules in the combined structure, the contribution of $\Delta t$ to the overall process $PIT$ is different. Therefore, the combination module needs to consider the following structure:

(a) Delayed structure

The delay type structure means that the modules are connected in series with each other, and the typical structure is shown in Fig. 3(a). Where $\Delta t_{A(IX)}$ refers to the response time of module A under the influence of the influence factor $IX$, and the similar expressions below have the same meaning. After module A fails, B will be disturbed (also shown in Figure 1(b)). Thus the combined response time $\Delta teq$ of this type of module:

$$\Delta teq = \Delta t_{A(IX)} + \Delta t_{B(IY)}$$  \hspace{1cm} (4)

In the actual industrial structure, the module is mainly a module with a backup power supply or an energy storage component, and the function can be guaranteed in the power supply time without affecting the subsequent modules.

(b) Competitive structure

Since there are multiple possible propagation paths for response information, there must be a competitive relationship between modules. Whether the modules are competitive or not depends on whether they have a common influence factor. The typical structure is shown in Figure 3(b). The response time $\Delta teq$ of this type of combined module:

$$\Delta teq = \min[\Delta t_{O(1X)}, \ldots, \Delta t_{O(nX)}]$$  \hspace{1cm} (5)

Among them, the module with the smallest response time is the path module that competes successfully. If the modules are in a completely competitive relationship, that is, their outputs act on the same module, when one module competes successfully, the other paths will be invalid.

(c) Conductive structure

The characteristic of the conductive structure is that the pre-module A does not affect the effectiveness of the input influence factor on the subsequent module B, but when A fails, it will give a failure signal to B, and its typical structure is shown in Fig. 3(c). The premise of this structure is that module A competes successfully. At this time, the response time of the module combination structure is related to the characteristics of module B.
4 Typical module response information flow analysis

Taking module A as ACC and module B as ASD as an example. At this time, IX and IY are voltage amplitudes V. When the trip condition is reached, the ACC instantaneously cuts off the circuit, causing the subsequent link to be interrupted.

For ASD, as shown in Fig. 4(a), when the ACC is not tripped, the terminal voltage of the ASD is $V_X$, and the time required for the fault to be at this time is the corresponding sag immunity time at $V_X$.

When the ACC trips, the ASD will fail after the corresponding immune time at the power interruption $V_y$. Since the VTC of ASD is approximately rectangular, the immunization time is basically the same under each amplitude. Therefore, regardless of whether the ASD failure is caused by the ACC tripping, the response time of the $V_X$ corresponding to the immune duration can be approximated, that is, the following relationship exists.

\[
\Delta t_{eq} = \Delta t_{eq}(V_X)
\]

However, for some devices, the VTC is not approximately rectangular, and the immunization time varies under each sag amplitude. Take ASD as module A and motor as module B as an example for analysis. When the load amount $T_m$ is constant, the driving torque $T_e$ is positively correlated with $u^2$, and the motor speed decreasing speed is related to the terminal voltage amplitude. However, when the voltage amplitude is lower than a certain threshold so that the ASD DC capacitor voltage is lower than the undervoltage protection threshold $V_{DCth}$, the ASD will block the output and the motor terminal voltage drops to zero. At this point, the motor speed will drop rapidly as the power supply is interrupted, as shown in Figure 4(b).

Therefore, theoretically, when the sag amplitude (defined by the effective value) is higher than the effective value of the pre-rectification voltage corresponding to $V_{DCth}$, the ASD does not have an additional influence on the subsequent modules and can be regarded as a conductive module. When the sag amplitude is lower than this value, the capacitance of the ASD can provide constant time support, so it can be regarded as a delay type module. At this point, the module group $\Delta t_{eq}$ can be recorded as:

\[
\Delta t_{eq} = \begin{cases} 
\Delta t_{eq}(V_X) & V > V_{th} \\
\Delta t_{eq}(V_{DCth}) & V < V_{th}
\end{cases}
\]
Figure 5 shows the response information flow topology of a system. In the figure, the block ABCD is four modules. The round blocks in and out are the initial and endpoints of the disturbance respectively. The connection between the modules indicates that there is a direct influence relationship between the two.

5 Simulation research

This paper simulates and reconstructs the above industrial processes in MATLAB/Simulink to verify the rationality and feasibility of the proposed scheme.

5.1 Model introduction

The whole process model structure is shown in Figure 6. The model consists of a sag source, ACC, ASD, motor, and furnace modules from left to right. Among them, the three-phase sag source model rated voltage is 380V, which can set the sag amplitude and duration of each phase separately; the ACC model is modeled according to the typical sag tolerance in [3]; ASD DC bus The capacitor is 4700μF with undervoltage protection; the furnace module is equipped with overheat protection with temperature parameters as monitoring values.

5.2 Process immunity assessment

5.2.1 Response Information Flow Assessment Program Results and Analysis

Combined with the research content in Section 2.3, each module protection type, trigger condition, and Δt determination method are as described in Table 2.
Table 2. Information of the equipment under test

| Module          | Type of protection       | Triggering conditions                                                                 | \( \Delta t \) |
|-----------------|--------------------------|----------------------------------------------------------------------------------------|----------------|
| ACC             | Loss of pressure protection | The sag event falls into the VTC trip zone                                               |                |
|                 |                          | When \( I_1 \) acts: the time when the sag occurs to the ACC trip (but it is a conductive module, so its \( \Delta t \) is not counted in the total duration) |                |
| ASD             | Undervoltage protection  | DC voltage is lower than 410V                                                           |                |
|                 |                          | When \( I_1 \) acts: the immune time under the corresponding sag amplitude;              |                |
|                 |                          | When \( I_{II} \) acts: the immune time when the power supply is interrupted;           |                |
| Furnace system  | Overheating protection   | Room temperature above 170 ° C (rated room temperature 160 ° C)                         |                |
|                 |                          | When \( I_1 \) acts: the immune time under the corresponding amplitude of the system;  |                |
|                 |                          | when \( I_{III} \) acts: the immune time when the power supply is interrupted.          |                |

Taking the most serious three-phase sag as an example, the simulation experiment is carried out on the V-ITC of each module under the condition that the sag amplitude is 0–0.9 \( V_n \) with 0.1 \( V_n \) as the step value and the sag duration is long enough. Simulation test. Each module immunity test platform is shown in Figure 7. Among them, the motor controller in the furnace simulation test platform is a very small and unprotected ASD module, which is only used for simulation analysis.

![Figure 7](image)

**Figure 7.** Test circuit of each model

The V-ITC curve data of each module under different torque \( T_m \) conditions are shown in Table 3. Where \(^*/^\) means that under the sag amplitude, the module is fully immune to the sag.
Table 3. V-ITC datasheet of modules

| V(p.u) | ACC | ASD | Furnace system |
|-------|-----|-----|----------------|
|       | 0.5T_m | 0.7T_m | 1.0T_m | 0.5T_m | 0.7T_m | 1.0T_m |
| 0.9   | /    | /    | /    | /    | /    | /    |
| 0.8   | /    | 0.215 | 0.152 | 0.076 | 0.215 | 0.152 | 0.076 | 0.108 | 43.63 | 37.23 | 33.94 |
| 0.7   | /    | 0.215 | 0.152 | 0.076 | 0.215 | 0.152 | 0.076 | 0.108 | 24.41 | 15.92 | 15.31 |
| 0.6   | 0.040 | 0.215 | 0.152 | 0.076 | 3.047 | 2.577 | 2.105 |
| 0.5   | 0.040 | 0.215 | 0.152 | 0.076 | 3.047 | 2.577 | 2.105 |
| 0.4   | 0.040 | 0.215 | 0.152 | 0.076 | 3.047 | 2.577 | 2.105 |
| 0.3   | 0.040 | 0.215 | 0.152 | 0.076 | 3.047 | 2.577 | 2.105 |
| 0.2   | 0.060 | 0.215 | 0.152 | 0.076 | 3.047 | 2.577 | 2.105 |
| 0.1   | 0.080 | 0.215 | 0.152 | 0.076 | 3.047 | 2.577 | 2.105 |
| 0     | 0.100 | 0.215 | 0.152 | 0.076 | 3.047 | 2.577 | 2.105 |

Taking the load torque of 0.7 T_m and the sag amplitude of 0.6 V_n as an example, the I derived from the sag source has an impact on the three modules at the same time. The ACC with the shortest immunization time is temporarily immune to the amplitude. When protected by ASD. It can be seen from Table 2 that Δt is the immune time of ASD corresponding to the sag amplitude, that is, 0.152 s. It can be seen from Fig. 6 that after the ASD fails, the furnace system will be affected by I_III, which constitutes the traditional delay type structure, and the furnace system Δt is the immune time when the power supply is interrupted, that is 2.105 s. According to the analysis in Section 2.4, the ASD and furnace system modules are considered as delay modules at this time (since the ACC is a conductive module, even if it is not faulty, its response time is not counted), so the PIT is the sum of the response times of the two is 2.729s. The response information propagation path and the corresponding immunization time under each amplitude are shown in Table 4.

Table 4. Propagation paths and their immunity time

| Working condition (T_m) | Amplitude (p.u.) | Path (0: sag source; 1: ACC; 2: ASD; 3: furnace system; 4: overheat protection system) | Immunization time (s) |
|------------------------|-----------------|--------------------------------------------------------------------------------|----------------------|
| 0.5T_m                 | 0-0.5           | 0→1→2→3→4                                                                      | 3.262                |
|                        | 0.6             | 0→2→3→4                                                                      | 3.262                |
|                        | 0.7             | 0→2→3→4                                                                      | 24.63                |
|                        | 0.8             | 0→3→4                                                                      | 43.63                |
| 0.7T_m                 | 0-0.5           | 0→1→2→3→4                                                                      | 2.729                |
|                        | 0.6             | 0→2→3→4                                                                      | 2.729                |
|                        | 0.7             | 0→2→3→4                                                                      | 16.07                |
|                        | 0.8             | 0→3→4                                                                      | 37.23                |
| 1.0T_m                 | 0-0.1           | 0→2→3→4                                                                      | 2.181                |
|                        | 0.2-0.5         | 0→1→2→3→4                                                                      | 2.181                |
|                        | 0.6             | 0→2→3→4                                                                      | 2.181                |
|                        | 0.7             | 0→2→3→4                                                                      | 15.39                |
|                        | 0.8             | 0→2→3→4                                                                      | 34.05                |

It can be seen from Table 4 that there are some differences between PIT and propagation paths under different working conditions. Among them, the smaller the load, the stronger the average immunity. For the case where the PIT is lower than 10s, the propagation path in the table is known to have a great relationship with the failure of ACC or ASD. At the same time, for the high-frequency sag with a sag amplitude higher than 0.6V_n, its PIT is generally higher, and it can immunize most of the sag events. This also means that it is not enough to use the PIT at the time of interruption to perform the sag loss assessment, which may make the result serious.
5.2.2 Traditional Immunization Assessment Program Results

The traditional evaluation scheme treats the process-side equipment or key sub-processes of interest as a whole object and obtains the PIT by recording the time-limited moments of key process parameters. The results obtained by the scheme are theoretically accurate. In this paper, the sensitive sub-process simulation platform shown in Figure 9 is simulated and tested. The furnace temperature limit is used as the process failure criterion. The results are shown in Table 5.

| Table 5. PIT obtained by traditional method 1 |
|---------------------------------------------|
| Amplitude (p.u.) | Immunization time (s) 0.5T<sub>m</sub> | 0.7T<sub>m</sub> | 1.0T<sub>m</sub> |
|-------------------|--------------------------|----------------|----------------|
| 0.8               | 42.21                    | 37.91          | 34.97          |
| 0.7               | 23.03                    | 17.21          | 15.34          |
| 0.6               | 3.036                    | 2.872          | 2.105          |
| 0.5               | 3.036                    | 2.872          | 2.105          |
| 0.4               | 3.036                    | 2.872          | 2.105          |
| 0.3               | 3.036                    | 2.872          | 2.105          |
| 0.2               | 3.036                    | 2.872          | 2.105          |
| 0.1               | 3.036                    | 2.872          | 2.105          |
| 0                 | 3.076                    | 2.872          | 2.105          |

5.2.3 Comparison of program results

Taking the whole process test plan as the standard, the relative error δ of the solution in this paper is shown in Table 6.

δ = \left| \text{PIT}_2 - \text{PIT}_1 \right| \times 100 \tag{8}

Among them, PIT1 is the result of the traditional method, and PIT2 is the evaluation result of the portable scheme proposed in this paper.

| Table 6. Relative error |
|-------------------------|
| Error and working condition | Corresponding torque maximum relative error of PIT under all amplitudes 0.5T<sub>m</sub> 0.7T<sub>m</sub> 1.0T<sub>m</sub> | Average relative error of PIT for each amplitude of corresponding torque 0.5T<sub>m</sub> 0.7T<sub>m</sub> 1.0T<sub>m</sub> |
| δ(%)                     | 7.44 | 6.62 | 3.61 | 5.91 | 4.46 | 2.19 |

It can be seen from Table 7 that the error obtained from the scheme and the whole process test scheme is small, so it has certain rationality.

6. Conclusion

(1) The method proposed in this paper fully considers the relationship between each module and process, can realize the modular evaluation of PIT, and improve the convenience of PIT acquisition.

(2) By comparing with the traditional scheme, the rationality of the method proposed in this paper is illustrated, and the evaluation of the immunity of the industrial process is relatively convenient and relatively accurate.

(3) The method of this paper can describe the disturbance propagation path under different sag and working conditions, which helps to develop a more targeted sloping treatment plan for users.

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