IOP Conf. Series: Materials Science and Engineering **231** (2017) 012007 doi:10.1088/1757-899X/231/1/012007

Security warning method and system for worker safety during live-line working

Chilong Jiang[1], Dehua Zou[1], Chenhai Long[1], Miao Yang[1], Zhanlong Zhang [2], Daojun Mei [2]

[1] Hunan Live Working Center of State Grid, Xingsha Economic and Technology District, Changsha, Hunan 410100, China
[1] Hunan Province Key Laboratory of Intelligent Live Working Technology and Equipment, Xingsha Economic and Technology District, Changsha, Hunan 410100, China
[2] State Key Laboratory of Power Transmission Equipment & System Security and New Technology (Chongqing University), Shapingba District, Chongqing 400030, China

Abstract. Live-line working is an essential part in the operations in an electric power system. Live-line workers are required to wear shielding clothing. Shielding clothing, however, acts as a closed environment for the human body. Working in a closed environment for a long time can change the physiological responses of the body and even endanger personal safety. According to the typical conditions of live-line working, this study synthesizes environmental factors related to shielding clothing and the physiological factors of the body to establish the heart rate variability index $RMSSD$ and the comprehensive security warning index SWI . On the basis of both indices, this paper proposes a security warning method and system for the safety live-line workers. The system can monitor the real-time status of workers during live-line working to provide security warning and facilitate the effective safety supervision by the live operation center during actual live-line working.

1 Introduction

In recent years, the rapid economic development and productivity growth have resulted in an increase in the number of people engaged in live-line working. To avoid physical damage, workers are required to wear shielding clothing upon entering the environment of live-line working. The shielding clothing allows the outer surface of the human body in a high-voltage electric field to form an equipotential shielding surface, thereby protecting the human body from harm caused by high-voltage electric fields and electromagnetic waves. However, shielding clothing acts as a closed environment for the human body. When a worker wears shielding clothing during live-line working, his/her metabolic rate increases; as a result, his/her body sweats continuously, and the temperature and humidity in the environment within the shielding clothing likewise change. This condition can induce heat stress, which results in a series of physiological responses, such as accelerated heart rate and increased core and skin temperatures. The National Institute for Occupational Safety and Health of the United States defines “heat stress” as the sum of the heat loads for the body from the environment and the human body itself; it can also be described as the extreme heat environment a human body suffers [1]. Heat stress can easily cause fatigue and energy dispersion, which can lead to heat-related illnesses and even death. Therefore, the main purpose of a security warning system is to understand the real-time status of a worker during live-line working and to provide early warning before the human body reaches the tolerance limit.

To realize the security warning for the safety of live-line workers, the tolerance of the human body to heat stress is considered. Therefore, an evaluation index to evaluate the real-time status of the human body is imperative. Moran et al. [2] proposed the physiological strain index (PSI), which assesses the heat stress intensity on a scale of 0–10. PSI reflects the intensity of heat stress in real time and analyzes the physiological state of a worker in a thermal environment. Lv [3] used the easily measured oral cavity temperature to replace rectal temperature, and proposed the physiological heat strain index (PHSI). PHSI analyzes the heat tolerance of the human body. However, PSI and $PHSI$ are not applicable to workers in the live-line working environment, as these two indices do not consider the environmental factors. Therefore, in this study, the actual conditions of live-line working are considered, and heart rate variability (HRV) is included to improve and optimize PSI . Furthermore, a security warning method and system for the safety of workers during live-line working are established, and the correctness and feasibility of the system was verified under actual work conditions.

2 Parameters of the security warning system for workers during live-line working

The thermal comfort of the human body is determined by six main factors. Four of these factors, namely, air temperature, air humidity, wind speed, and average radiation temperature are related to the environment, and the other two factors are metabolic rate and thermal resistance of clothing [4]. Live-line workers in shielding clothing are unaffected by air velocity and radiation, and thermal resistance is nearly constant. Only the temperature and humidity in the environment within the shielding clothing need to be considered. Body temperature and heart rate represent the metabolic rate. On the basis of the actual conditions of measurement, that is, the device for data acquisition is incorporated in the shielding clothing and measurement can only be done outside the human body, the parameters of the security warning system are human skin temperature (chest), heart rate, the temperature within the shielding clothing, and the humidity within shielding clothing.

2.1 Human skin temperature

Skin temperature can be used to evaluate the intensity of heat stress. The average skin temperature is maintained at approximately 35 °C. To dispel body heat, the body temperature mediation system transfers body heat from the deep tissue to the skin. This process maintains the normal body temperature through heat exchange with the external environment. When a human is in a high-temperature and high-humidity environment or he/she performs high-intensity work, the amount of dissipated heat is highly restricted. As a result, the skin temperature increases. When the skin temperature approaches the core temperature, the human body has reached the tolerance limit of heat stress, and the person should immediately stop working.

According to the experimental results in Reference [5], a low thermal resistance of clothing (the thermal resistance of the clothing in the experiment was 0.1 clo) results in minimal differences in the sample temperatures of the chest and forehead in an environment with a temperature of 28 °C. The experimental environment is similar to the internal environment within the shielding clothing. Table 1 compares the temperature of the forehead and the core temperature. Under normal conditions, forehead temperature should be approximately 2 °C lower than the core temperature.

Table 1: The comparison table of body's forehead temperature and the core temperature (Data is for reference only)

The forehead temperature(°C)	34	35	35.6	35.8	36	36.2	36.4	37
The core temperature(°C)	36.2	37	37.5	37.7	37.8	38.0	38.1	38.5

2.2 Heart rate

Heart rate is sensitive to environment changes, and it can be measured easily and rapidly. Thus, this factor is widely used in the evaluation of human body states. Intense physical labor can increase heart rate. In addition, human body temperature increases in a high-temperature and high-humidity environment, such as shielding clothing. An increase in body temperature can cause rapid heartbeat because of the promoted blood circulation of the body to eliminate waste heat. If no appropriate measure is implemented, the increases in body temperature and heartbeat rate can be deleterious to human health. The normal heart rate is usually within the range of 60–120 times/min, and the limit of worker heart rate is set at 180 times/min in a high-temperature environment [6].

2.3 Temperature within the shielding clothing

Air temperature is the main factor affecting human thermal comfort, and it directly affects the heat exchange between the human body and the external environment. Perspiration increases when the water vapor pressure at a constant skin temperature increases with increasing air temperature. Thus, the subjective thermal sensation of a person is developing toward the direction of heat. The human body is very sensitive to air temperature. An environment temperature higher than 42 °C is not conducive for people at work or otherwise.

2.4 Humidity within the shielding clothing

The effect of air humidity on the thermal comfort of the human body is related to the air temperature. When the air temperature is within the range of 20 °C–25 °C and the air humidity changes from 30%–85%, the thermal sensation of the human body is minimally affected. However, a higher air temperature moistens the skin, and the heat-dissipating capacity of the body by evaporation depends on the air humidity. At this time, air humidity becomes the main factor affecting the human thermal sensation [4]. The air humidity limit is 100%.

3 Security warning method for worker safety during live-line working

3.1 Establishment of the security warning indices

Security warning index (*SWI*) was established to estimate human body status. The root mean square successive difference (*RMSSD*) as the HRV index was used to monitor HRV according to the parameters of the security warning system for workers during live-line working.

3.1.1 Comprehensive security warning index SWI . Finding an appropriate evaluation index is necessary to evaluate the real-time body status of workers during live-line working and to determine whether the body reaches the warning level with respect to the relevant threshold. However, the safety indices for the human body are related to environmental factors (temperature and humidity) and body physiological factors (body temperature and heart rate). These indices are independent of each other, and they are mutually influenced, No single index could fully describe the state of the human body. Therefore, an index to evaluate the human body state should be comprehensive and objective.

PSI by Moran et al. is expressed as follows:

$$PSI=\frac{5\left(T_{ret}-T_{re0}\right)}{\left(39.5-T_{re0}\right)}+\frac{5\left(HR_i-HR_0\right)}{\left(180-HR_0\right)} \qquad (1)$$

In Equation (1), T_{ret} and HR_i are the rectal temperature and the heart rate of the human body, respectively, at any time; T_{re0} and HR_0 are the rectal temperature and the heart rate of the human body, respectively, at the initial time.

$PHSI$ by Lv is expressed as follows:

$$PHSI=\frac{5\left(T_{oi}-T_{o0}\right)}{\left(39.5-T_{o0}\right)}+\frac{5\left(HR_i-HR_0\right)}{\left(180-HR_0\right)} \qquad (2)$$

In Equation (2), T_{oi} and HR_i are the oral cavity temperature and the heart rate of the human body, respectively, at any time; T_{o0} and HR_0 are the oral cavity temperature and the heart rate of the human body, respectively, at the initial time.

Equation (1) and Equation (2) only consider the physiological factors of the body. For the workers in shielding clothing during live-line working, the shielding clothing acts as a closed environment. Therefore, the temperature and the humidity within the shielding clothing greatly influence the physiological factors of the body, except for body temperature and heart rate. Therefore, in the proposed method, the PSI by Moran et al. is extended and optimized by adding two internal environmental parameters, namely, temperature and humidity within the shielding clothing. At the same time, the location of the measurement device is considered by using the skin temperature of the chest, which is more easily measured than the rectal temperature. SWI for live-line working is obtained by combining the internal environmental factors and the body's physiological factors. SWI is expressed as follows:

$$SWI = \frac{2.5\left(T_{si} - T_{s0}\right)}{\left(37.5 - T_{s0}\right)} + \frac{2.5\left(HR_i - HR_0\right)}{\left(180 - HR_0\right)} + a\frac{T_a}{42} + b\frac{RH}{100\%} \quad (3)$$

In Equation (3), T_{si} and HR_i are the skin temperature of the chest and the heart rate of the human body, respectively, at any time during live-line working; T_{s0} and HR_0 are the skin temperature of the chest and the heart rate of the human body, respectively, at initial time during live-line working; T_a and RH are the temperature and humidity within the shielding clothing, respectively, and are measured at the same time as T_{si} and HR_i.

The skin temperature of the chest, T_s, is approximately 2 °C lower than the core temperature under normal conditions; thus, the limit value of the skin temperature of the chest is set to 37.5 °C. The limit of the heart rate is 180 bpm, whereas the limit values of the temperature and humidity within the shielding clothing are 42 °C and 100%, respectively. The relation between a and b is assumed to be $a+b=5$ to ensure that the value of SWI is in the range of 0–10 and the state of the human body can be characterized.

In Reference [7], the analytic hierarchy process was used to analyze air temperature, velocity, humidity, and average radiation temperature, and the weights of these factors in the evaluation of thermal environment were 0.5091, 0.3012, 0.1270, and 0.0627, respectively. For the internal environment of the shielding clothing, the weight value is normalized by disregarding wind velocity, average radiation temperature, and the other factors. The ratio of the temperature to the humidity within the shielding clothing is 0.8:0.2. Consequently, $a=4$ and $b=1$.

Therefore, the calculation formula form the comprehensive security warning index SWI is:

$$SWI = \frac{2.5\left(T_{si} - T_{s0}\right)}{\left(37.5 - T_{s0}\right)} + \frac{2.5\left(HR_i - HR_0\right)}{\left(180 - HR_0\right)} + \frac{4T_a}{42} + \frac{RH}{100\%} \quad (4)$$

3.1.2 Index of heart rate variability $RMSSD$. The heart rate is sensitive. Even if SWI does not reach the warning level, the heart rate may surge. The events of HRV may cause arrhythmia in serious situations. Therefore, the security warning method for worker safety during live-line working needs to consider equalization of the heart rate, in addition to using the comprehensive security warning index SWI. HRV refers to the small differences between successive intervals, and it can be analyzed by measuring the changes in the consecutive normal QRS complexes in the same period that appeared in the electrocardiogram (i.e., the change in the continuous RR interval) [8]. Thus, $RMSSD$ is the root mean square of the difference between the adjacent RR intervals. When the value of the heart rate is 60/RR interval, the formula of $RMSSD$ is

$$RMSSD=\sqrt{\frac{(\frac{60}{X_1}-\frac{60}{X_2})^2+(\frac{60}{X_2}-\frac{60}{X_3})^2+(\frac{60}{X_3}-\frac{60}{X_4})^2+\ldots+(\frac{60}{X_{n-1}}-\frac{60}{X_n})^2}{n-1}} \quad (5)$$
$$=60\sqrt{\frac{\sum_{i=2}^{n}(\frac{1}{X_{i-1}}-\frac{1}{X_i})^2}{n-1}}$$

In Equation (5), $X_1, X_2, X_3, \cdots, X_{n-1}, X_i$ are the values of the heart rate recorded at a certain frequency for a period.

3.2 Determination of index threshold

Derived from Equation (2) and Equation (4), $SWI \approx \frac{PHSI}{2}+4\frac{T_a}{42}+\frac{RH}{100\%}$. The experimental samples of severe labor and moderate labor in Reference [3] are used to calculate the maximum SWI value, which refers to the samples who can adhere to 4 hours of labor, and the minimum SWI value, which refers to samples who cannot adhere to 4 hours of labor at a given period, as shown in Figure 1 and Figure 2.

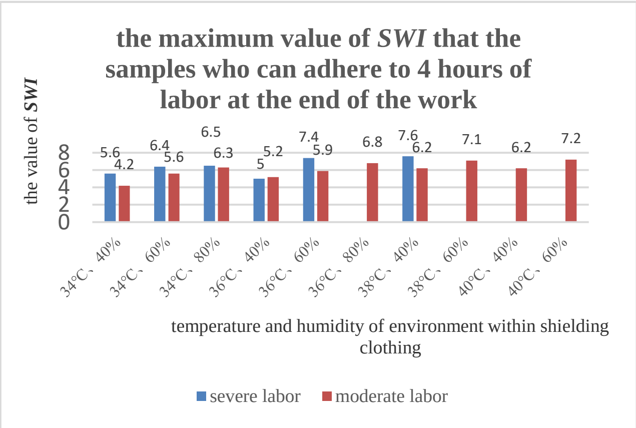

Figure 1: The maximum value of SWI that the samples who can adhere to 4 hours of labor at the end of the work

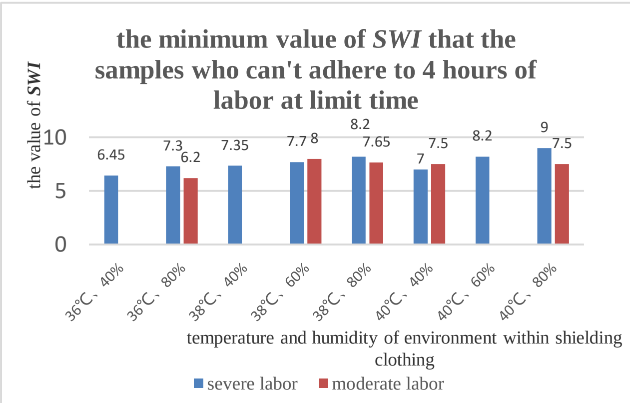

Figure 2: The minimum value of SWI that the samples who can't adhere to 4 hours of labor at limit time

Owing to the individual differences of the experimental samples, the approximate scopes of the warning can be obtained according to Figures 1 and 2. In the system, $SWI>8$ is designated as the C_3-level warning state of SWI, $SWI>7$ is designated as the C_2-level warning state of SWI, and $SWI>6$ is designated as the C_1-level warning state of SWI.

The normal values of $RMSSD$ in relation to gender, age, and heart rate, are shown in Table 2, Table 3, and Table 4, respectively.

Table 2: The relationship between the value of $RMSSD$ and gender in normal human [9]

gender	The normal value of $RMSSD$（ms）
male	38.8±15.4
female	39.3±14.6

Table 3: The relationship between the value of $RMSSD$ and age in normal human [9]

Age group	The normal value of $RMSSD$（ms）
Under 20 years of age	52.9±17.2
aged between 20 and 30	45.7±14.1
aged between 30 and 40	41.6±13.3
aged between 40 and 50	34.3±13.9
aged between 50 and 60	31.6±11.5
Over 60 years of age	32.0±17.6

Table 4: The relationship between the value of $RMSSD$ and the value of heart rate in normal human [9]

the value of heart rate	The normal value of $RMSSD$（ms）
Less than 60 times/min	54.0±22.9
60~80 times/min	38.7±14.9
more than 80 times/min	38.7±14.9

This system runs on a worker in a live-line working environment. The live-line working population generally comprises males aged 25–45 years old. In addition, the normal heart rate is generally 60 times/min or above. Thus, 39.0ms ± 15.0 ms is selected as the normal reference value of $RMSSD$. In the environment of live-line working, when workers wear shielding clothing to work, increased metabolism may result when the heart rate increases. Therefore, only the upper limit value of warning needs to be considered. That is, when $RMSSD > 54$ ms, the possibility of HRV needs to be considered. At this time, the state of the human body is designated as HRV state.

3.3 Realization of the security warning method

According to the monitored values of SWI and $RMSSD$ for the workers during live-line working, alarm levels are determined on the basis of the priority evaluation of HRV. The C_1-level warning state of SWI raises a C_1-level alarm, which reminds the workers not to work for an extended period. The C_2-level warning state of SWI raises a C_2-level alarm, which reminds workers to take a proper rest. The HRV state and C_3-level warning state of SWI raise a C_3-level alarm, which forces workers to stop working and rest. The flowchart of the security warning method is shown in Figure 3.

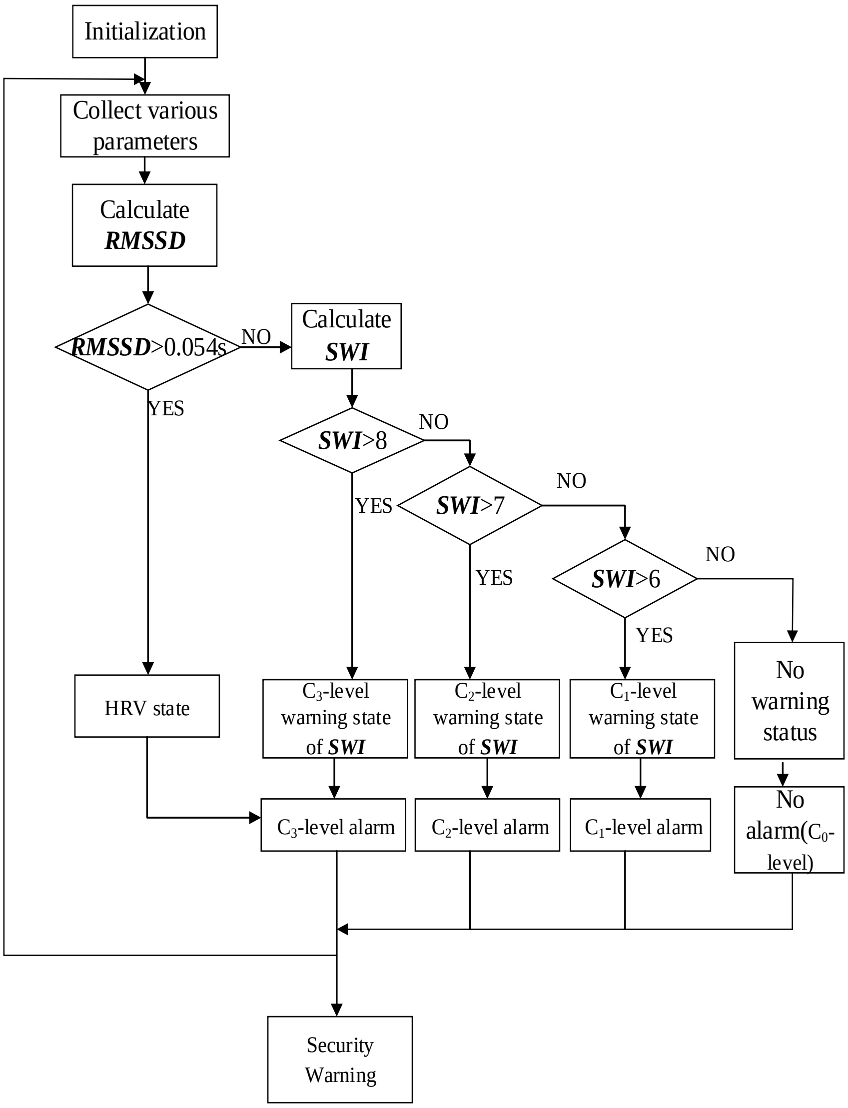

Figure 3: The flowchart for realization of the security warning method

4 Security warning system and its application

4.1 Structure of the security warning system

A security warning system for worker safety is incorporated in the shielding clothing, as shown in Figure 4. The block diagram of the security warning system is shown in Figure 5.

Figure 4: Shielding clothing in live-line working

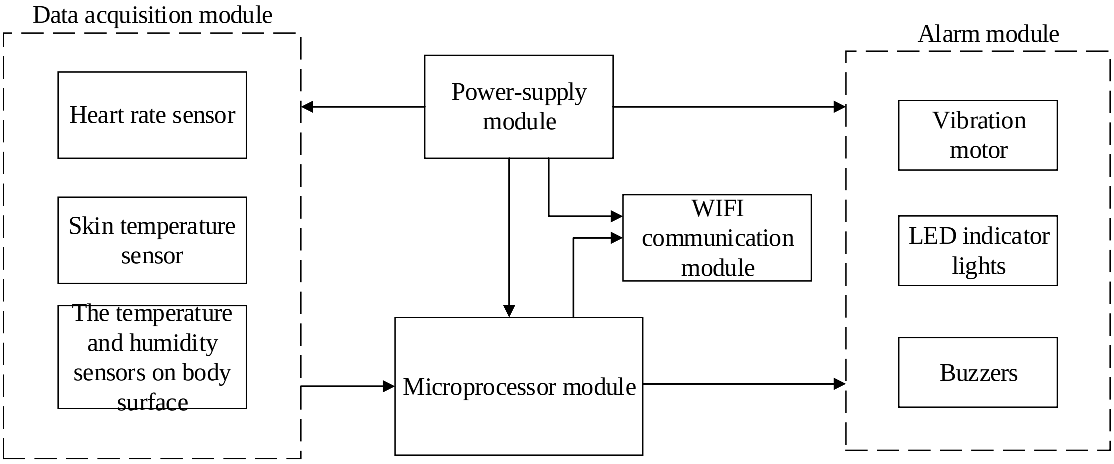

Figure 5: The block diagram for structure of security warning system

As shown in Figure 5, the security warning system is composed of heart rate sensor, a skin temperature sensor, the temperature and humidity sensors on the body surface, a microprocessor, a vibration motor, LED indicator lights, buzzers, Wi-Fi communication device, and other modules. The electrodes of the heart rate sensor are mounted on the back of the belt, and the belt is worn on the chest near the heart to obtain the heart rate. A skin temperature sensor is installed at the back of the system to collect the skin temperature of the chest, as shown in Figure 6. The temperature and humidity sensors on the body surface are installed in front of the system to collect temperature and humidity within the shielding clothing, as shown in Figure 7.

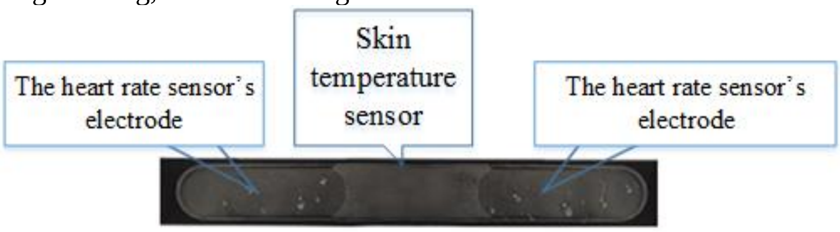

Figure 6: The appearance view of the back of security warning system

Figure 7: The appearance view of the front of security warning system

The microprocessor records and analyzes the collected data and calculates the real-time monitored values of SWI and $RMSSD$. For the calculation of $RMSSD$, the system selects the sampling length of 2 min at a frequency of 0.1 Hz to record the successive values of heart rate: $X_i, X_{i-1}, X_{i-2}, \cdots, X_1$ (where X_i is the value of heart rate collected at the current time, X_{i-1} is the value of heart rate collected last time, and so on). Compared with threshold values of SWI and $RMSSD$, the alarm level for the worker at the current time is determined and sent to the field monitoring site through the Wi-Fi communication device. The system drives the vibration motor, LED indicator lights, and buzzer alarm depending on the alarm level.

4.2 Application analysis
At present, the system has been used in the related live-line working center of the State Grid Hunan Electric Power Company. The actual data of a worker during live-line working are used to verify the effectiveness and practicability of the proposed method and system. The collected skin temperature of the chest and the heart rate of the human body at the initial time before live-line working are $T_{s0} = 34.1\,°\text{C}$ and $HR_0 = 76\,\text{bpm}$, respectively. After the shielding clothing is worn, the real-time data of the 10 groups of workers during live-line working are collected. These data include the skin temperature, T_{si}; heart rate, HR_i; temperature, T_a; and the humidity within the shielding clothing, RH. The data are shown in Table 5.

Table 5: The real-time data of the worker in live-line working

Parameter \ Group	1	2	3	4	5	6	7	8	9	10
T_{si} (°C)	34.1	34.2	34.5	34.7	34.8	35.1	35.3	35.4	35.6	35.7
HR_i (*bpm*)	76	87	94	106	109	112	116	122	128	129
T_a (°C)	31.1	31.3	32.0	32.8	33.2	33.4	33.9	34.2	34.5	34.9
RH	42%	48%	53%	61%	65%	67%	69%	71%	72%	75%

The SWI values for the data of the 10 groups are calculated as follows using Equation (4): **SWI**= (1.16, 1.56, 2.02, 2.55, 2.75, 3.07, 3.34, 3.59, 3.89, 4.03). Therefore, the operator’s own state has not reached the level of alarm.

At the same time, the heart rate values of the workers during live-line working within 2 min are recorded at a frequency of 0.1 Hz: **HR**= **X**= (81, 87, 85, 89, 96, 95, 101, 104, 107, 109, 106, 111, 116). According to Equation (5), at the time of $RMSSD\text{=}0.029s < 0.054s$, the workers did not indicate HRV. Therefore, the workers during live-line working are in a safe state, and the security warning system will not alarm.

5 Conclusions

This paper proposes a security warning method for worker safety during live-line working. The four evaluation parameters are skin temperature of chest, heart rate, the temperature within the shielding clothing, and the humidity within the shielding clothing. The PSI by Moran and colleagues was improved and optimized to form a comprehensive security warning index SWI suitable for a live-line working environment. Furthermore, the index of HRV, namely, $RMSSD$, is proposed to signal an auxiliary warning based on body condition. The formation of a complete security warning system can prevent protect workers from life-threatening working condition and reduce the occurrence of work accidents. In actual application, technical and safety problems have not occurred. The security warning system for worker safety during live-line working is characterized by compact structure, convenient wearing, high reliability, and high sensitivity. The system can provide a reliable safety warning for workers during live-line working and assist the live-line working center in safety supervision.

References

[1] National Institute for Occupational Safety and Health. “Working in Hot Environments”, IEEE Transactions on Power Apparatus and Systems, PAS-88(7), pp. 1061-1069, (1969).

[2] Daniel S. Moran, Avraham Shitzer, Kent B. Pandolf. “A Physiological Strain Index to Evaluate Heat Stress”, American Journal of Physiology, 275(44), pp. 129－134, (1998).

[3] Shilei Lv. “Research on Human Heat Tolerance under Extreme Heat Environment”, Tianjin University, (2006).

[4] Zhiwei Lian, Haiyan Feng. “Comprehensive Fuzzy Evaluation on Indoor Thermal Environment”, Journal of HV&AC, 31(5), pp. 15-18, (2001).

[5] Hao Zhou. “Experimental Study on the Influence Factors of Human Skin Temperature”, Xi`an University of Architecture and Technology, (2013).

[6] Jia Liu. “Research on Human Physiological Parameters and Weights Impact under Extreme Hot and Humidity Environment”, Tianjin University, (2011).

[7] Xiaoying Ou, Shengqiang Yang, Baohai Yu, et al. “Evaluation of Thermal Environment in Mine and Its Application”, Journal of China University of Mining & Technology, 34(3), pp. 324-326, (2005).

[8] Haozhu Chen. “Measurement of Heart Rate Variability and Its Clinical Significance”, Journal of Clinical Eletrocardiology, 3(4), pp. 168-172, (1994).

[9] Dakai Wang. “Analysis of Time Domain of Heart Rate Variability (HRV) among Healthy Subjects”, Hainan Medical Journal, 12(8), pp. 20-21, (2001).