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Research on Failure Diagnosis Model of Key Equipment in the Electric Traction System of a Bullet Train

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As for the failure diagnosis problem of the transformer of traction system of the bullet train, the model-based diagnosis method is introduced to the failure diagnosis of traction transformer of the bullet train in this paper, and the failure diagnosis scheme based on the combination of model diagnosis and fuzzy Petri network is also proposed. Two-layer model for the structure and function of traction transformer is set up, so that the minimum conflicts candidate set can be searched offline, and the minimum conflicts set can be identified online, thus the external failure diagnosis of the traction transformer can be achieved. As for the internal failure diagnosis, the model-based diagnosis is applied to the positioning of failure elements of the traction transformer; and the fuzzy Petri network is used for regional knowledge representation so as to ratiocinate and achieve the internal failure diagnosis. The analysis is implemented with the failure data of three-phase V/X wiring transaction-transformer of the bullet train as the example; and the diagnosis result is the verification for the feasibility and effectiveness of transaction-transformer failure diagnosis scheme based on the integration of model diagnosis and fuzzy Petri network.

1. Introduction

Since the construction of Beijing-Tianjin inter-city high-speed railway from2005, with ten-year construction and development of high-speed railway, the high-speed railway of China has been pushed forward continuously; and currently, the operating mileage of high-speed railway ranks the first in the world (Ahlem et al., 2013). The safe operation of bullet train is not only related to the safety of passengers, but also is of significance to the development of national economy. The loss caused by operation failure of bullet train is very huge each year in China; in addition, large amount of cost incurred in daily repair and maintenance of bullet train also takes a large share in the train transportation expenses (Brenna et al., 2012). At the same time of rapid development, how to maintain the high-speed and stable operation of the bullet train in the more and more complicated rails conditions has been the key point for the work implemented by railway departments. With the continuous operation of special passenger line of high-speed railway, the operation scale of bullet train has been enlarged continuously, and relevant changes occur in the quantity of dispatched train, rate of traffic flow and operation conditions (Raygani et al., 2013); however, the failure diagnosis of the bullet train can promote the bullet-train operation management, emergency responses and safety guarantee; therefore, the importance of failure diagnosis of the bullet train must be attached. The electric traction system is the most important system in the railway operation, including the traction power-supply system and traction drive system; the electric traction system is the key for system electricity and power ensuring the normal operation of the bullet train (Li et al., 2013). The traction transformer is the key equipment in the traction power-supply system and traction drive system, the normal and stable operation of which is related to the reliable operation of the entire electric traction system directly (Song et al., 2013); in the meanwhile, the structure and operation environment of the traction transformer can make it the equipment with most failure frequency, therefore, the prevention and diagnosis of relevant failures of traction transformer must be paid with more attention.

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2. Modelling of traction transformer of the bullet train

2.1 Principle analysis and element abstraction of traction transformer

The Figure 1 is the schematic diagram for the three-phase VX-wiring traction transformer. The three-phase VX-wiring traction transformer substantially consists of two single-phase three-winding transformers put in the same fuel tank (Giorgio et al., 2013). ABC is the three-phase circuit of the electrical power system, and the TRF is the leading-out terminal for the overhead line system of the edge connection of the transformer, the grounding and positive feeder separately.

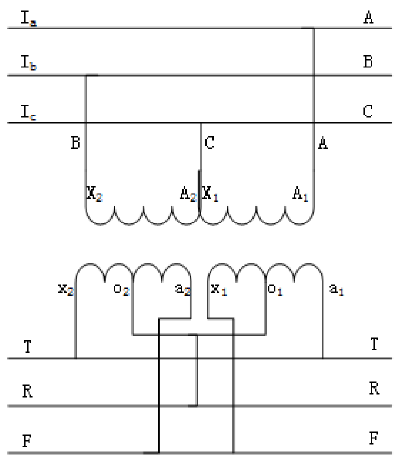

Figure 1: Schematic Scheme for Three-phase VX-wiring Traction Transformer

The modelling of the traction transformer is achieved based on the abstraction on elements; however, the traction transformer system can be considered as consisting of the inlet-outlet line, winding and iron core. The current and voltage transformer only be applied to supervise the system status information (Xia et al., 2017), thus the failure occurrence possibility of current and voltage transformer is not considered, based on which the data obtained from measurement are deemed as the right data. Therefore, the abstract elements of the traction transformer mentioned move are as follows: {T_11, T_21, T_1, T_12, T_22, T_12, T_21}; in which, the T_11 and T_21 means the primary sides of two single-phase transformers separately, which are deemed as the independent small element models. T_1 means the entity formed by the primary side of two single-phase transformers, which is the large element model, T_11 and T_21 are the small elements inside it. T_12 and T_22 means the secondary side of two single-phase transformers, which are also the independent small element models; T_12 and T_21 are the large element models of the secondary side of the single-phase transformer, and the relevant small elements inside which are T_12 and T_22.

2.2 Calculation of equivalent circuit

The VX-wiring three-phase traction transformer is equal to two single-phase three-winding transformers; the power supply of the right and left power-supply arms can be achieved with two equivalent single-phase transformers (He et al., 2014). The principle of two single-phase transformers are the same; three taps—T, F and N on the secondary side are connected to the overhead line system, the outlet end of positive feeder and the grounding end separately. Take one single-phase transformer of which as the example, the equivalent circuit diagram is shown in Figure 2.

In which, the Zab is the equivalent short-circuit impedance of the primary winding, Zm is the short-circuit impedance converted to the primary side; Zfn is the short-circuit impedance of F winding converted to the primary side, and Ym is the equivalent excitation admittance converted to the primary side. Assume that the above traction transformer is the ideal transformer, and if the transformation ratio is set up as converted to the primary side, then parameters of the equivalent circuit can be calculated based on rated parameters on the transformer nameplate, see the details in Table 1.

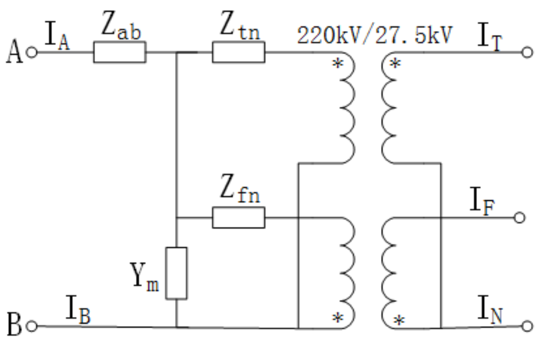

Figure 2: Equivalent Circuit Diagram for Single-phase Traction Transformer

Table 1: The Residual Value of Each Analytical Redundancy Relationship

Name	Z_{ab}/Ω	Z_{tn}/Ω	Z_{fn}/Ω	Y_m/(10^{-7}S)
T_1	3.524+j101.64	5.506+j101.64	14.094+j101.64	4.959-j25.826
T_2	4.659+j127.05	7.280+j127.05	18.034+j127.05	4.339-j20.661

2.3 Modelling of Traction Transformer of the Bullet Train

2.3.1 Normal model of single-phase transformer

If the voltage value of each port of the single-phase transformer and the current value flowing into each port are as follows separately: □□

Ia: Current value flowing into the transformer from A phase; Ib: Current value flowing into the transformer from B phase; It: Current value flowing out the transformer from T end; Ir: Current value flowing out the transformer from R end; If: Current value flowing out the transformer from F end; Vab: Voltage value between phase A and B; Vtr: Voltage value of TR port; Vrf: Voltage value of RF port; k: Rated voltage ratio on the primary and secondary side.□□

According to the definition and equivalent circuit diagram of above variables, see the constrained relationshi between the voltage and the current in equation 1 and 2 when the single-phase traction transformer is in normal operation (Song et al., 2016).

$$
\begin{aligned}
&I_A + I_B = 0\\
&I_T + I_F + I_N = 0\\
&I_A = \frac{I_T}{k} \quad \frac{I_F}{k} + (\frac{I_T}{k} \ Z_m + k \ V_m) \ Y_m
\end{aligned}
\tag{1}
$$

$$
V_{AB} = I_A \ Z_{ab} \quad \frac{I_F}{k} \ Z_{fn} + k \ V_{FN} \tag{2}
$$

VTF

3. Failure diagnosis of traction transformer of the bullet train

3.1 Principle introduction to MBD and fuzzy Petri network

Based on the model diagnosis (MBD) (Ali et al., 2016), the modelling thought is to set up the network topology model of and among elements based on the structure and function of elements of the system, to achieve the modelling with systematic “deep knowledge” (Xiao et al., 2017). See the basic thought in Figure 3. Knowledge about the model can be obtained directly based on the object principle, in which the accumulation process of the knowledge is omitted, and the disadvantage of traditional artificial intelligent technology is conquered; in the meanwhile, the realization of modelling and diagnosis of the system is implemented separately and independently, which make the better independence and portability of the method based on models; however, it is subject to the problems in handling the uncertainty and association relation among components (Dai et al., 2015).

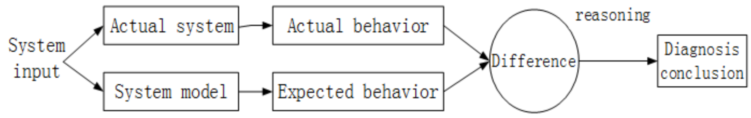

Figure 3: The Basic Idea of MBD

As the fuzzy Petri network is added with fuzzy factors, which can be used to describe and analyse uncertain problems effectively (Wang et al., 2015), and also conquers the defects of traditional Petri network in handling fuzzy proposition; the knowledge presentation and diagnosis inference can be achieved in imaging way in the failure diagnosis of transformer (Li et al., 2014). Based on the thought of complementary integration, the inter-combination of MBD and fuzzy Petri is applied to the failure diagnosis of traction transformer of the bullet train in this paper.

3.2 Identification of fault elements

If the Phase A of T1 outlet-end of the traction transformer is subject to grounded short circuit, then Table 2 means the monitoring value of current and voltage transformer under such circumstance based on simulation, and V_11_A means the primary-side phase-A voltage of the first single-phase transformer, the rest measuring values are subject to the same naming methods.

The monitoring value of transformer in Table 2 is substituted into the analytical redundant relations for calculation, and relevant residual error in Table 3 is obtained. As the accuracy of transformer model can be affected due to the existence of transformation ratio in the actual operation (Alonso et al., 2013), the transformer measuring value is substituted into the analytical redundant relations under the normal conditions so as to correct the analytical redundant relations with larger residual errors; as for the process mode of this paper, the residual error of such analytical redundant relations is multiplied with 10-5, which can improve the interference of model accuracy on inference and diagnosis.

The allowable relative residual threshold in this paper is set up as 0.3, and Table 3 shows that the minimum conflict candidate set with relative residual error larger than 3 is {MinCSC7}, and the corresponding fault element is {T_11}; as only one minimum conflict candidate set exists, thus it is the minimum hitting set; therefore, according to the consistent judgement of normal model of traction transformer, the fault element is the primary side for the first single-phase traction transformer (T1).

Table 2: Traction Transformer Monitoring Value in Fault Conditions

Measurements	Amplitude	Phase angle
V_11_A	0	0
V_11_B	2.1943×10^5	-120.01
V_21_C	2.1939×10^5	119.99
V_11_AB	2.1943×10^5	59.99
V_21_BC	3.8003×10^5	-90.01
V_12_TN	2.7389×10^4	59.81
V_12_FN	2.7391×10^4	-120.18
V_22_TN	4.7436×10^4	-90.19
V_22_FN	4.7438×10^4	89.81
I_A	3.4750×10^4	-81.87
I_B	7.5558	-63.30
I_C	4.9463	127.59
I_12_T	1.2685	14.74
I_12_F	2.3166	-165.15
I_12_N	1.0481	14.99
I_22_T	2.1970	-135.27
I_22_N	1.8152	-135.01
I_22_F	4.0121	44.85

Table 3: The Residual Value of Each Analytical Redundancy Relationship

The smallest conflict	Absolute residual value	Maximum value	Relative residual value
MinCSC1	1.200×10^{-9}	2.856×10^{0}	4.202×10^{-10}
MinCSC2	2.236×10^{-9}	4.946×10^{0}	4.521×10^{-10}
MinCSC3	1.258×10^{-4}	2.317×10^{0}	5.429×10^{-5}
MinCSC4	1.887×10^{-4}	4.012×10^{0}	4.704×10^{-5}
MinCSC5	4.780×10^{0}	5.478×10^{4}	8.726×10^{-5}
MinCSC6	1.950×10^{-5}	9.487×10^{4}	2.055×10^{-10}
MinCSC7	5.763×10^{1}	5.659×10^{1}	1.018×10^{0}
MinCSC8	8.012×10^{1}	7.841×10^{6}	1.022×10^{-5}
MinCSC9	6.494×10^{2}	2.194×10^{5}	2.959×10^{-3}
MinCSC10	1.101×10^{3}	3.800×10^{5}	2.896×10^{-3}

3.3 Fault type diagnosis

In order to identify the fault type of the fault element quickly, the occurrence possibility of various faults can be assumed based on experience generally; the occurrence possibility of disconnection fault is set up at 0.1, and the occurrence possibility of short circuit fault is set up at 0.3, and the occurrence possibility of grounding fault is set up at 0.6 (Wang et al., 2014). The fault match is implemented according to the fault possibility in the MBD abductive inference (Bin et al., 2015), the maximum fault mode of fault possibility is matched firstly; in case it fails in matching, then the fault mode with the secondary possibility is matched, the rest can be done in the same manner (Hiroshi et al., 2015). The fault element is fixed, and the grounding fault match should be implemented firstly to the fault element {T_11}(Cao et al., 2014); if the match is successful, then the fault type is {[T_11,{groundA}]}(Cen and Stewart, 2017), which is the primary-side phase-A grounding of the first single-phase traction transformer(Chen et al., 2012).

4. Conclusion

The iron traction transformer is the research object of this paper, and the discussion about the fault diagnosis realization of the traction transformer of the bullet train is carried out; a new fault diagnosis method which can be applied to the traction transformer of the high speed railway has been developed through exploration – the fault diagnosis method based on model diagnosis and fuzzy Petri network integration; the realization of the diagnosis mainly includes the separate diagnosis on external fault and internal fault. According to the internal and external fault modelling and simulation verification of three-phase V/X-wiring traction transformer of a traction transformer of the high-speed line, the result of which indicates that the fault diagnosis based on the model diagnosis and fuzzy Petri integration can be used to diagnose the traction transformer fault accurately.

Reference

Ahlem B.Y., Sejir K.E., Ilhem, S.B., 2013, State Observer-Based Sensor Fault Detection and Isolation, and Fault Tolerant Control of a Single-Phase PWM Rectifier for Electric Railway Traction, Browse Journals Magazines, 28(12), 5842-5853, DOI: 10.1109/tpel.2013.2257862

Ali C., Walter L., Rochdi T., 2016, Comparison of energy management strategies of a batterysupercapacitors system for electric vehicle under real-time constraints, Applied Energy, 163, 190-200, DOI: 10.1016/j.apenergy.2015.11.020

Brenna M., Foiadelli F., 2012, Analysis of the Filters Installed in the Interconnection Points Between Different Railway Supply Systems, IEEE Transactions on Smart Grid, 3,551-558, DOI: 10.1109/TSG.2011.2162860

Cao W., He B., Shen W., Shi X., Wu K., Okamoto T., Suzuoki Y., 2014, An approach for economic assessment on oil-paper insulation diagnosis through accelerated aging experiments, IEEE Transactions on Dielectrics and Electrical Insulation, 21, 1842-1850, DOI: 10.1109/TDEI.2014.004370

Cen Z., Stewart P., 2017, Condition Parameter Estimation for Photovoltaic Buck Converters Based on Adaptive Model Observers, IEEE Transactions on Reliability, 66, 148-160, DOI: 10.1109/TR.2016.2618320

Chen Z., Zhang Q., Jiao F., Chen R., Wang K., Chen M., Liu S., 2012, Study on the Reliability of Application-Specific LED Package by Thermal Shock Testing, Failure Analysis, and Fluid --Solid Coupling Thermo-Mechanical Simulation, Packaging and Manufacturing Technology IEEE Transactions on Components, 2, 1135-1142, DOI: 10.1109/TCPMT.2012.2190934

Dai H., Guo P., Wei X., Sun Z., Wang J., 2015, ANFIS (adaptive neuro-fuzzy inference system) based online SOC (State of Charge) correction considering cell divergence for the EV (electric vehicle) traction batteries, Energy, 80, 350-360, DOI: 10.1016/j.energy.2014.11.077

Giorgio C., Daniele C., Mario P., 2014, Modeling and Simulation of an Isolated Hybrid Micro-grid with Hydrogen Production and Storage, Energy Procedia, 45, 12-21, DOI: 10.1016/j.egypro.2014.01.003

He L., Xiong J., Ouyang H., Zhang K., 2014, High-performance indirect current control scheme for railway traction four-quadrant converters, IEEE Trans. Ind. Electron., 61(12), 6645–6654, DOI: 10.1109/tie.2014.2316240

Li H., Zhang K., Zhao H., Fan S., Xiong J., 2013, Active power decoupling for high-power single-phase PWM rectifiers, IEEE Trans. Power Electron., 28(3), 1308-1319, DOI: 10.1109/tpel.2012.2208764

Li Q., 2014, Electric matching problems in traction power supply system, Electr, Railway, 3, 13-16. DOI: 10.1109/tmee.2011.6199346

Raygani S.V., Tahavorgar A., Fazel S.S., Moaveni B., 2012, Load flow analysis and future development study for an AC electric railway, IET Electrical Systems in Transportation, 2, 139-147, DOI: 10.1049/iet-est.2011.0052

Roberto C., Davide D.B., Matteo M., 2014, Model based Design and Optimization of a Fuel Cell Electric Vehicle, Energy Procedia, 45, 71-80, DOI: 10.1016/j.egypro.2014.01.009

Song W., Feng X., Smedley K.M., 2013, A Carrier-Based PWM Strategy with the Offset Voltage Injection for Single-Phase Three-Level Neutral-Point-Clamped Converters, IEEE Transactions on Power Electronics, 28, 1083-1095, DOI: 10.1109/TPEL.2012.2210248

Song W., Ma J., Zhou L., Feng X., 2016, Deadbeat predictive power control of single-phase three-level neutral-point-clamped converters using space-vector modulation for electric railway traction, IEEE Trans. Power Electron., 31(1), 721–732, DOI: 10.1109/tpel.2015.2400924

Wang H., Wu M., Sun J., 2015, Analysis of Low-Frequency Oscillation in Electric Railways Based on Small-Signal Modeling of Vehicle-Grid System in dq Frame, IEEE Transactions on Power Electronics, 30(9), 5318-5330, DOI: 10.1109/tpel.2015.2388796

Wang S., Song W., Zhao J., Feng X., 2016, Hybrid single-carrier-based pulse width modulation scheme for single-phase three-level neutral-point-clamped grid-side converters in electric railway traction, IET Power Electron., 9(13), 2500–2509, DOI: 10.1049/iet-pel.2015.0656

Wang X., Blaabjerg F., Wu W., 2014, Modeling and analysis of harmonic stability in an AC power-electronics-based power system, IEEE Trans. Power Electron., 29(12), 6421-6432, DOI: 10.1109/tpel.2014.2306432

Xia J.H., Guo Y., Dai B., Zhang X., 2017, Sensor Fault Diagnosis and System Reconfiguration Approach for an Electric Traction PWM Rectifier Based on Sliding Mode Observer, IEEE Transactions on Industry Applications, 53(5), 4768-4778, DOI: 10.1109/tia.2017.2715816

Xiao F.D., Min D., Tong Z., 2017, Comprehensive comparison between silicon carbide MOSFETs and silicon IGBTs based traction systems for electric vehicles, Applied Energy, 194, 626-634, DOI: 10.1016/j.apenergy.2016.05.059