International Journal of Future Generation Communication and Networking
Vol. 8, No. 2 (2015), pp. 33-44
http://dx.doi.org/10.14257/ijfgcn.2015.8.2.04

A Novel Synchronous Switch Method Based on Kalman Filter

Zheng Guilin and Chen Xi

(School of Power and Mechanical Engineering, Wuhan University, Wuhan, 430072, China)

Abstract

In order to create the idea of AC switch without electric arc and inrush voltage to the power system, the study of accurately catches AC zero crossing of a mechanical relay is put forward in this paper. It is the key to make the switch act at the right predicted time which realizes switch on or off exactly at the AC zero crossing point. However, the action time of a mechanical switch is affect by many factors such as driving voltage, ambient temperature, age of the mechanic structure. Aim at the discrete measurements of latching relay action time, the Kalman filter mathematic model is introduced in this paper to eliminate the dynamic noise and measurement noise which affects the bias time drift from the zero voltage or zero current point. Simulation result by matlab and group data get from experiments of a realized multichannel switch indicate that Kalman filter algorithm can overcome the discreteness of latching relay action time measurements. Also confirmed by statistical experiments that synchronous switch action precisely and reliably at AC zero point which can ensure the ability of suppress electric arc and high frequency inrush current.

Keywords: *synchronous switching, latching relay, zero voltage switching (ZVS), zero current switching (ZCS), Kalman filter mode*

1. Introduction

A traditional electric switch generates high frequency inrush current since the high voltage directly adds on load when it is turned on. Meanwhile it may also produce arc once it is turned off while current is not zero at the moment [1]. Inrush current in the load and the arc in the switch are not what expected because it not only shorten the load life and especially arc burning greatly impact on the contactor's conductivity and it is the main reason that a switch generally has a very short safe working life span. In sever case, arc might lead to the contactor stick together and fail to separate again. In this paper, a smart synchronous switch technology is proposed to solve the above problems.

Synchronous switch is to let the switch acts at the AC voltage or AC current zero crossing time which overcomes the voltage shock to the load at switch on and electric arc between the switch contactor at switch off [2-3]. It is an advanced technology to make the switch much longer life than the traditional one.

2. Synchronous Switch Principle

2.1. Introduction of Synchronous Switching

Synchronous switch is a new kind smart switch which synchronizing the switching pace to the AC zero crossing under the controlling of Micro Processor Unit (MPU) to mechanical execution switches inside [4]. In order to control the switch by electric pulse, power latching relay is chosen as the mechanical execution switch. Latching relay is based on mechanic contactor, it has advantage of lower power consumption, and excellent

ISSN: 2233-7857 IJFGCN

feature in power switch application in situation of overvoltage, over current. And it needs not any heat sink.

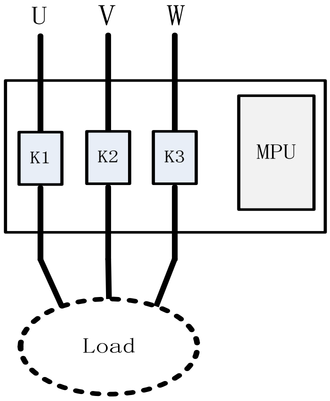

Figure 1. Diagram of Synchronous Switch

As shown in Figure 1. There are three latching relays inside the three-phase synchronous switch which controls the U, V and W phase. The function of MPU is to detect voltage or current zero crossing point, process control commands and predicate the next action time. Synchronous switch combines traditional mechanical switch and MPU technology.

2.2. Principle of Synchronous Switching

In smart synchronous switch, the main function of MPU is to catch the cycle T of ACpower and zero crossing point of each phase. Because there is several milliseconds delay t_s(for easier description, set$t_s = t_{on} = t_{off}$, where t_{on}means the delay when the switch turns on, whilet_{off}means the delay when the switch turns off) between command send from MPU and execute by mechanical device, so the command sending time must be$t_s$ahead the next AC zero point whichcan ensure the switch acts accurately at the power zero crossing point [5-6].

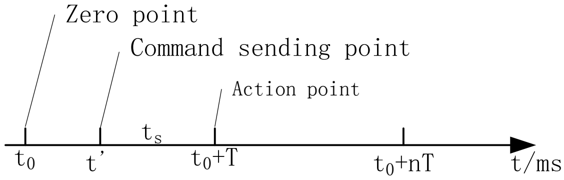

Figure 2. Sequence Diagram

As shown in Figure 2. If the first zero point ist_0, the period of the AC power is$T$, so the next zero point is $t_0 + T/2$.According to the characteristics of the switch action delay timet_s,which is measured normally less than 6 ms, MPU calculates the command sending time$T/2 - t_s$, namely at timet'.After$T - t_s$from zero point, MPU sends control command to the mechanical execution unit. Then after time t_s, the switch could execute the order at the zero point [7].

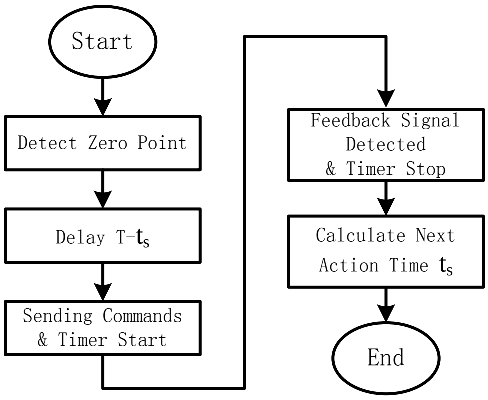

Figure 3. Workflow Diagram

The workflow of synchronous switch is shown in Fig.3. The switch on and off workflow are both the same. The t_s is the action time which includes switch on action time and switch off action time. The control command is sent after$T - t_s$from zero point, meanwhile, the timer starts to work. The feedback signal is detected to indicate the switch progress finish. Then the timer stops and calculates the present action time, also predicts the next action time.

However, different environment and temperature as well as the times the switch is used are all factors to impact the delay time slightly. As a result, the action time of each switch is not consistent. Besides, it is not good to test the delay time one by one in manufacture, That is to say the action time of each switch has to be confirmed by self-learning during the work. The real action time can be expressed as follows [8-9]

$$t_k = \bar{t} + \Delta t_k$$
(1)

Where, $t_k$is the execution time of each switch measured by the$k$times. It contains two parts$\bar{t}$andΔt_k. $\bar{t}$is the average action time of the switch, Δt_k is the drift time compare with the average time. Thus, a dynamic correction math model mechanism is needed for synchronous switch to amend the action time in order to ensure zero point switching in various environments.

3. Hardware Design

3.1. AC Zero Detection Circuit Design

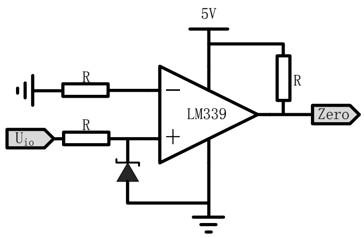

Figure 4. Circuit of Zero Point Detection

As shown in Figure 4. Zero detection circuit is used for detecting zero point potential between contacts. The input Uio is the differential voltage of the power of contacts. In order to deliver the output zero signal to 5V power supply MPU, the power of zero point detection circuit is also designed to be 5V.Besides, 5.1V stabilivolt is used of the reference voltage of compactor LM339's input voltage. The AC signal turns to zero signal output when AC goes to negative, the input and output wave is shown in Figure 5.

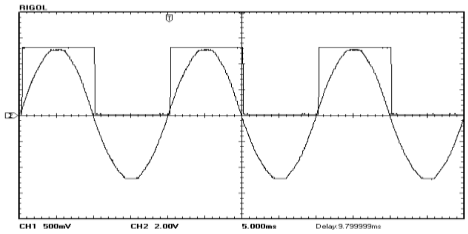

Figure 5. Zero Detection Experiment Wave

In Figure 5, sinusoidal signal is the sample of AC voltage input signal, and the pulse signal is the zero output signals. There is almost no phase shift between input and output signal. Hence, when the zero point of one phase is detected, the zero point of other two phases can be speculated by MPU based on the principle of three phases AC power.

3.2. Action Feedback Circuit Design

Action feedback circuit uses for measure switch action time.

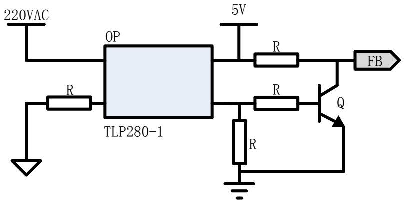

Figure 6. Circuit of Action Feedback

As shown in Figure 6. The action feedback circuit takes sample from the output of switch. When switch is on, AC current flow through bidirectional optocoupler, the output signal changes to pulse signal from high level signal.

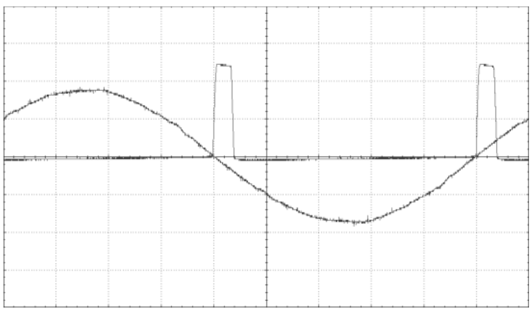

Figure 7. Action Feedback Circuit Experiment Wave

As shown in Figure 7. Due to the minimum current value is needed to make the bidirectional opt coupler work and the triodeQ1 need minimum base-on drive current, there is a short period off work time t_c around zero point for optocoupler and triode. Speculated from experiments, the fixed deviation t_c is $1ms$ which can be corrected by algorithm to get the true value.

4. Kalman Filter Model

4.1. Principle of Kalman Filter

Kalman filter is an optimization regression data processing algorithm. Its principle is to use the dynamic information of the target to get rid of the influence of noise and get an ideal state estimation of the target [10]. Kalman filtering is a recursive estimation algorithm, which can be applied to calculate the estimation of current states long as obtain the last moment state estimation and the current state observed value, so there is no need to record observations or estimates of historical value. Meanwhile, it is a pure time-domain filter it is not like those frequency domain filter which needs to calculate in frequency domain first then transformation to the time domain [11-12]. The basic idea is: the use of space model of signal and noise, with the last moment estimate value and current state observations, to update state variables estimation, and then get the current accurate estimate value. Its advantage is to eliminate random noise, so as to approach the useful information [13].

4.2. Algorithm of Kalman Filter

Due to some inevitable factors, the measured action time of all mechanical switches has certain discreteness. As shown in Figure 8.

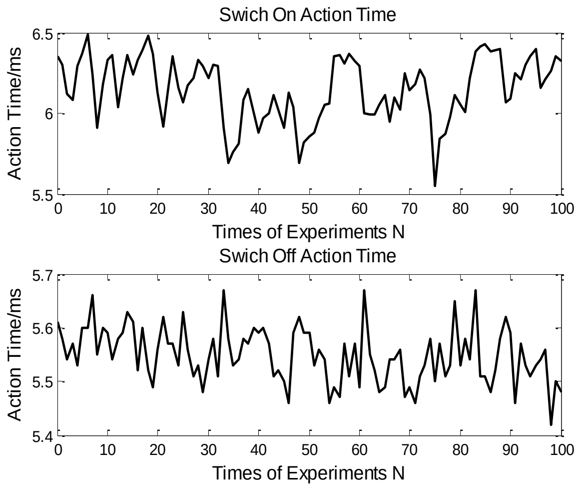

Figure 8. Action Time of Latching Relay

In Figure 8, there are 100 times for switch on and off records graph of action time. As can be seen from the graph, there isn't any law to follow no matter in switch on action or in switch off action. In this case, the accuracy of switch at zero point cannot be ensured.

Thus, in order to overcome the discrete action time of mechanical switch, and to adapt the environment changes which affect the action time, this article adapt Kalman filter model to predict the optimal action time.

The three-phase synchronous switch contains three latching relays. T_{on} is the switch on action time, and T_{off} is the switch off action time. The state equation of system can conclude as[14-16]:

$$X_k = \Phi_{k,k-1} X_{k-1} + \Gamma_{k-1} U_{k-1} + w_{k-1} \quad (2)$$

Where X_k are the state variables; $\Phi_{k,k-1}$ and Γ_{k-1} is state transition matrix; U_k is system controlling quantity; w_{k-1} is system noise.

Thus, state vector is defined as

$$X_k = \begin{bmatrix} T_{on1_k} & T_{off1_k} \\ T_{on2_k} & T_{off2_k} \\ T_{on3_k} & T_{off3_k} \end{bmatrix} \quad (3)$$

The T_{on1_k}, T_{on2_k} and T_{on3_k} represent estimate switch on action time of the three latching relays, while T_{off1_k}, T_{off2_k} and T_{off3_k} represent estimate switch off action time of the three latching relays.

Theoretically, the relay action time is fixed. So, assuming the k moment action time and $k-1$ moment action time are the same. The state transition matrix is defined as

$$\Phi = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (4)$$

Because there is not system controlling quantity, $U_k = 0$. Then state equation simplified as:

$$X_k = \Phi_{k,k-1} X_{k-1} + w_{k-1} \quad (5)$$

The system measured value is the observed value. So the observe matrix can also defined as unit matrix, namely $H = \Phi$.

Thus, the k moment system observation equation can express as

$$Y_k = H_k X_k + v_k \quad (6)$$

$$\boldsymbol{Y_k} = \begin{bmatrix} Y_{on1_k} & Y_{off1_k} \\ Y_{on2_k} & Y_{off2_k} \\ Y_{on3_k} & Y_{off3_k} \end{bmatrix} \quad (7)$$

Where Y_{on1_k}, Y_{on2_k} and Y_{on3_k} represent observe switch off action time of the three latching relays, while Y_{off1_k}, Y_{off2_k} and Y_{off3_k} represent observe switch off action time of the three latching relays. H_k is observe matrix; v_k is measurement noise.

Assuming system noise w and observation noise v are zero mean noise, mutual independence, and meet the normal distribution. Its statistical characteristics are as follows

$$E(w_k) = E(v_k) = 0 \quad (8)$$

$$con(w_k, w_j) = E(w_k w_j^T) = R_k \delta_{kj} \quad (9)$$

$$con(v_k, v_j) = E(v_k v_j^T) = Q_k \delta_{kj} \quad (10)$$

$$R_k = var(w_k) = E(w_k w_j^T) \quad (11)$$

$$Q_k = var(v_k) = E(v_k v_j^T) \quad (12)$$

Where Q_k is the covariance of system noise, R_k is the covariance of observation noise.

The Kalman filter algorithm can split into two steps. Firstly, using the optimal estimation of last moment to predicate the current state $\hat{X}_{k,k-1}$ and covariance $P_{k,k-1}$,

$$\hat{X}_{k,k-1} = \Phi_{k,k-1} \hat{X}_{k-1} \quad (13)$$

$$P_{k,k-1} = \Phi_{k,k-1} P_{k-1} \Phi_{k,k-1}^T + Q_k \quad (14)$$

Then calculate the Kalman gain Kg_k. According to the current state to calculate the next optimal estimation value $\hat{X}_k$, and update the system covariance P_k.

$$Kg_k = \frac{P_{k,k-1}H_k^T}{H_k P_{k,k-1} H_k^T + R_k} \quad (15)$$

$$\hat{X}_k = \hat{X}_{k,k-1} + Kg_k(Y_k - H_k \hat{X}_{k,k-1}) \quad (16)$$

$$P_k = (\mathrm{I} - Kg_k H_k)P_{k,k-1} \quad (17)$$

Every time the optimized estimate value $\hat{X}_k$of$k$moment is obtained, the Kalman filter algorithm takes $\hat{X}_k$and$P_k$as exist conditions, and repeat these steps to make operation continuous [17-22].

5. Simulation and Experiment

5.1. Simulation of Kalman Filter

According to the datasheet of latching relay, it has a million times of electrical life. Hence, the test program is designed to measure the action time of latching relay once after every 1000 times of switch action which includes switch on action time and switch off action time. There are three lathing relays in one synchronous switch are been test. 200 groups of data for each latching relay are obtained. So, the test last 200,000 times for each relay.

In order to make Kalman filter work, the initial state and covariance are set as$\hat{\mathrm{X}}_0 = 5\mathrm{ms}$, $\mathrm{P}_0 = 50$. The simulation results are shown in Figures 9-11.

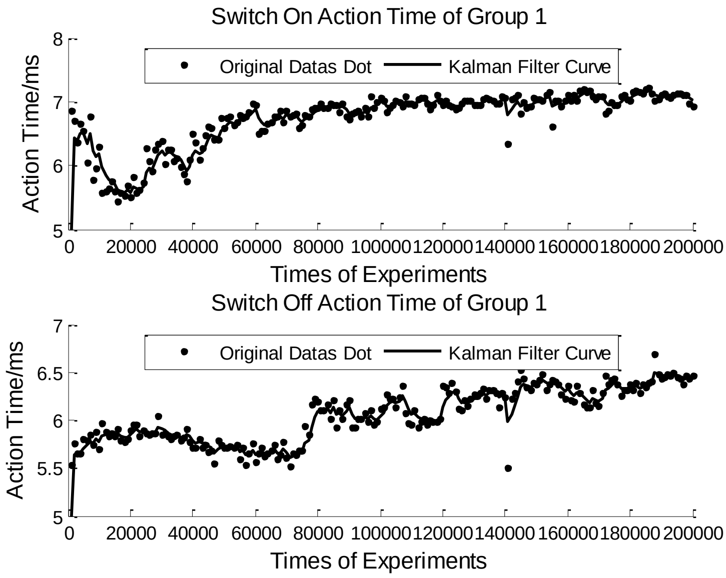

Figure 9. Simulation of Second Latching Relay

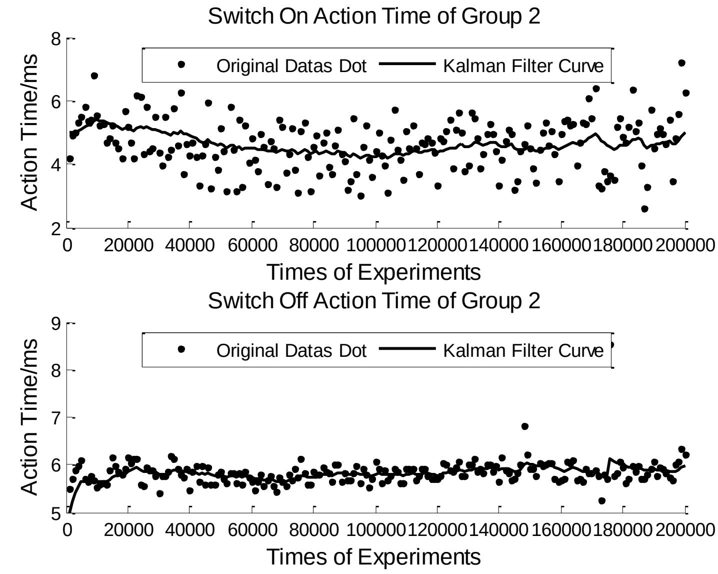

Figure 10. Simulation of First Latching Relay

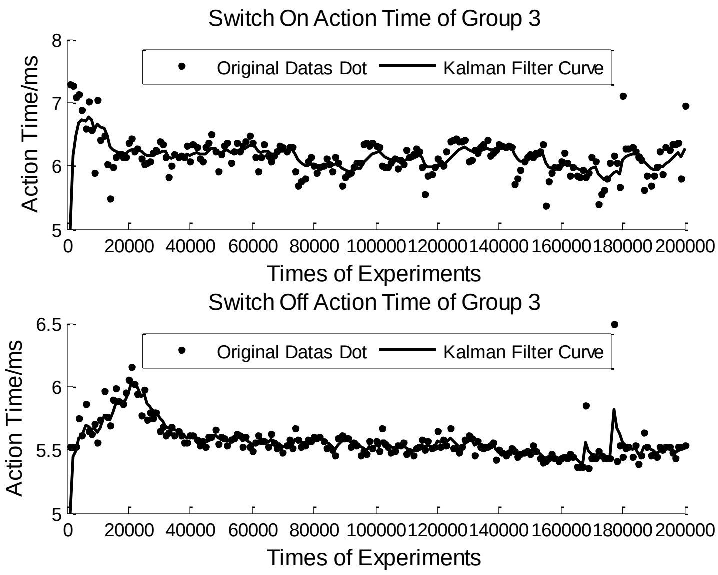

Figure 11. Simulation of Third Latching Relay

In Figures 9-11, dots represent the original measured data, and the curves represent the output data of the Kalman filter. Although the same initial values are given, the outputs are fast convergence to real action time of three different latching relays. Despite the fact that the action of first one fluctuates a little at the beginning, the others are very stable. As shown in the graph, the original data has larger discreteness whether switch on or switch off of action time. However, after processed by Kalman filter, the prediction outputs are much relatively stable. Moreover, it can follow the trends of original measured data.

5.2. Experiment of Zero Switching

In order to testify the effect of Kalman filter to the accuracy of zero point switching, a contrast experiment was designed. The test program controls one latching relay of synchronous switch act 200 times, then using the oscillograph to record the voltage wave when switching. One group use the Kalman filter, while another group doesn't.

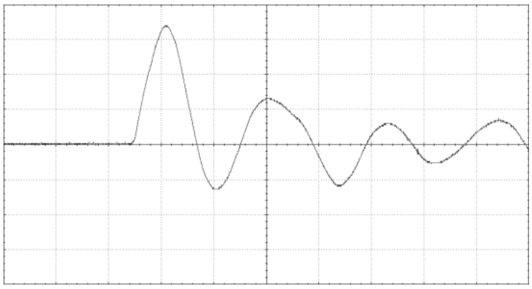

Figure 12. Current Wave of Switch On

The curve shown in Figure 12 is the load current wave when switch on at voltage zero point. Although the inrush current still exists, the inrush current is much lower than ever.

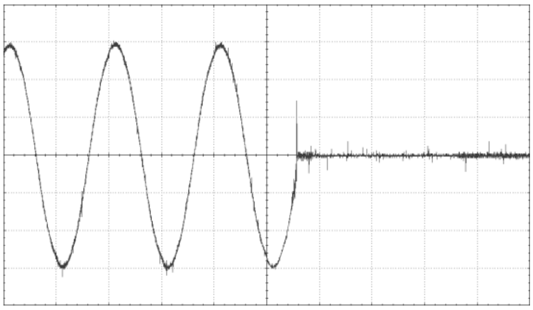

Figure 13. Current Wave of Switch Off

The curve shown in Figure 13 is the load current wave when switch off at current zero point.

According to the statistics of the phase position deviation of zero point switching, the phase position deviation of probability density distribution chart was drawn.

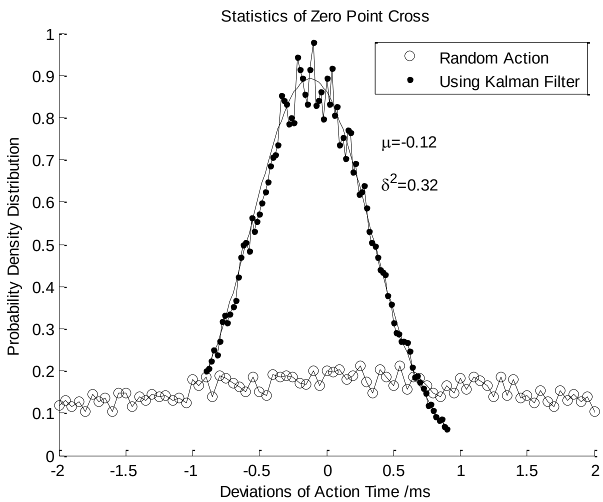

Figure 14. Statistics of Phase Position Deviation

The curve with circles in Figure 14 is the probability density distribution of random switching experiment, and the curve with dots in Figure 14 is the probability density distribution of Kalman filter switching experiment. In the random switching process, every switching is mutual independence. Thus, the probability density distribution curve of random switching closes to the uniform distribution curve. However, the probability density distribution of Kalman filter switching follows Gaussian distribution. The 90% part of the deviations concentratein$\pm 0.5ms$. By using curve fitting, the expectation and variance are obtained. Where expectationμis-0.12, varianceσ^{2}is0.32. In conclusion that the deviation of zero point switching with Kalman filter algorithm is decreased greatly, and the accuracy of zero point switching is considerably improved.

6. Conclusion

In order to solve the inconsistency of mechanical switch action time, and to ensure the accuracy of zero point switching, this action time prediction method based on Kalman filter model is proposed. Simulation results show that this model can forecast the action time and improve its accuracy.

Confirmed by the experiments, by using the Kalman filter model, the 90% of the deviations are concentrate in . The experiments prove that mechanical switch can also realize zero point switching. Meanwhile, the inrush current and electric arc are both improved greatly.

Acknowledgements

This work is supported by the following foundations: National Natural Science Foundation of China (61272114), the 2013 annual funding project of state oceanic administration, Marine renewable energy projects (GHME2013JS01); Guangdong Marine economic innovation development demonstration area special projects (GD2012-C03-006).

References

[1] L. Jiaomin, “Arc Motion Mechanism and Simulation of Low Voltage Electrical Switch”, Science Press, Beijing, **(2013)**.
[2] D. Fuhua, D. Xiongying and Z. Jiyan, “An Intelligent Reactive Power Compensator Based on Synchronous Vacuum Circuit Breaker”, Proceedings of the CSEE, vol. 35, no. 30, **(2005)**.
[3] Z. Hao and H. Renjie, “A Synchronous Switching Device for Reactive Power Compensation Capacitor Based on Closed-loop Current Control”, Power System Protection and Control, vol. 40, no. 129, **(2012)**.
[4] L. Yiping, H. Xiangyang and N. Haijiao, “Development of Synchronous Switching Device for Capacitor Bank Based on Permanent Magnet Switch”, High Voltage Apparatus, vol. 48, no. 24, **(2012)**.
[5] H. Kim, C. Yoon and S. Choi, “A Three-Phase Zero-Voltage and Zero-Current Switching DC–DC Converter for Fuel Cell Applications”, IEEE Transactions on Power Electronics, vol. 25, no. 391, **(2013)**.
[6] B. R. Lin and J. Y. Dong, “Analysis and Implementation of An Active Clamping Zero-voltage Turn-on Switching/zero-current Turn-off Switching Converter”, IET Power Electronics, vol. 3, no. 429, **(2010)**.
[7] B. Delfino, F. Fornari, C. Gemme and A. Moratto. “Power Quality Improvement in Transmission and Distribution Networks via Synchronous Switching”, Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference, (**2001)**, Atlanta, GA.
[8] N. T. Quang, H. J. Chiu, Y. K. Lo, and M. M Alam, “Zero-voltage Switching Current-fed Fly back Converter for Power Factor Correction Application”, IET Power Electronics, vol. 6, no. 1971, **(2013)**.
[9] Y. Ye, K. W. E. Cheng, J. Liu and C. Xu, “A Family of Dual-Phase-Combined Zero-Current Switching Switched-Capacitor Converters”, IEEE Transactions On Power Electronics, vol. 29, no. 4209, **(2014)**.
[10] X. Guohui and X. Hui, “A Study of Variance Estimation of Kalman Filtering Method”, Engineering Journal of Wuhan University, vol. 37, no. 28, **(2004)**.
[11] L. Haiyan, L. Weijia and H. Yunba, “Multisensory Measured Data Fusion Based on Kalman Filter”, Engineering Journal of Wuhan University, vol. 44, no. 521, **(2011)**.
[12] Z. Zhengyu, L. Lin and C. Ming. “Short-term Traffic Flow Forecasting Model Combining SVM and Kalman Filtering”, Computer Science, vol. 40, no. 248, **(2013)**.
[13] L. Dawei, J. Pengfei and L. Weiguo, “A kind of Integrated Navigation and Control System Design for Substation Robot Based on The Kalman Filtering and Fuzzy Algorithm”, CAAI Transactions on Intelligent Systems, vol. 8, pp. 226, **(2013)**.
[14] Q. Minghui, T. Zhenggui and Y. Bo, “Application of Self-adaptive Kalman Filter in Bridge’s Health Monitoring System”, Noise and Vibration Control, vol. 33, no. 141, **(2013)**.

[15] L. Li, Z. He, T. Yufa and X. Guotai. "Application of Adaptive Kalman Filter in Geomagnetic Attitude Detection System", Acta Armamentarii, vol. 34, no. 1155, **(2013**).
[16] A. Sinha, T, Kirubarajan and Y. Bar-Shalom, "Application of the Kalman-Levy Filter for Tracking Maneuvering Targets", IEEE Transactions on Aerospace and Electronic Systems, vol. 43, no. 1099, **(2007)**.
[17] W. Xiaotian, Y. Zhijia, W. Yingnan and W. Zhongfeng, "Application of Dual Extended Kalman Filtering Algorithm in The State of Charge Estimation of LithiumIon Battery", Chinese Journal of Scientific Instrument, vol. 34, no. 1732, **(2013)**.
[18] J.C. Peng and N.C. Nair, "Enhancing Kalman Filter for Tracking Ring down Electromechanical Oscillations", IEEE Transactions on Power Systems, vol. 27, no. 1042, **(2012)**.
[19] M. H. Kim and S. Lee. "Kalman Predictive Redundancy System for Fault Tolerance of Safety-Critical Systems", IEEE Transactions on Industrial Informatics, vol. 6, no. 46, **(2010)**.
[20] E. Ghahremani and I. Kamwa. "Dynamic State Estimation in Power System by Applying the Extended Kalman Filter With Unknown Inputs to Phasor Measurements", IEEE Transactions on Power Systems, vol. 26, no. 2556, **(2011)**.
[21] G. Valverde, and V. Terzija, "Unscented Kalman filter for power system dynamic state estimation" IET Generation, Transmission & Distribution, vol. 5, no. 29, **(2011)**.
[22] C. Mitsantisuk, K. Ohishi, and S. Katsura, "Estimation of Action/Reaction Forces for the Bilateral Control Using Kalman Filter", IEEE Transactions on Industrial Electronics, vol. 59, no. 4383, **(2012)**.

Authors

Zheng Gui-lin, is a Professor in the Department of Automation Wuhan University, Wuhan, China. He obtained his PhD in electrical engineering from the Wuhan University in 1989. His research work has centered on control theory and engineering, measurement and sensors, mechanical–electrical system integration, intelligent power grids, and related fields.

Chen Xi, is now working towards the Ph.D. degree in the Department of Automation, Wuhan University, Wuhan, China. His research interests are intelligent power grids techniques and networking optimizes technology.