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Influence of Fast Fluctuation of Dynamic Load Current on Dynamic Error of Smart Electricity Meter

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Abstract – This paper is concerned with the influence of the dynamic error of smart electricity meter (hereinafter referred to as smart meter) in the condition of dynamic current. Firstly, the random fluctuation of the dynamic load current amplitude is analysed and two typical run lengths are found out. Secondly, dynamic models of every unit in the smart meter are established. These models reflect the dynamic transfer relationship between the input and output signals of every unit. Thirdly, the dynamic errors of smart meter are simulated and analysed in the condition of dynamic current with typical run lengths. Finally, we verify the simulation results by experiment with On-Off-Key (OOK) dynamic test current signal. The result shows that the gain feedback switching of programmable gain amplifier (PGA) unit leads to the dynamic current signal clipping in dynamic current conditions, and the signal clipping is the main source of the dynamic error of smart meter. Moreover, the dynamic error of the short-time run length of dynamic current is larger than the long-time run length.

Keywords – dynamic load, run characteristic, smart energy meter, dynamic error

I. INTRODUCTION

With the development of modern industry, more and more high-power equipment is put into use, and therefore bring rapid fluctuation of dynamic load current with large range. In the dynamic current conditions, some electrical energy meters that have passed error test at steady state current condition can even appear significant dynamic errors [1], and seriously affect the transaction of electric energy.

In the past decades, as for analysis and evaluation of the smart meter errors have received great attention and some research results have been obtained. Reasons for errors in the PGA range switching mechanism of smart meter was analysed in the presence of harmonics under steady state load condition [2-3]. However, the influence level of PGA unit in the smart meter under dynamic load condition cannot be appraised. In terms of power measurement errors, to improve the accuracy of electric energy measurement, many measurement algorithms have been studied in recent years, for example, some approaches based on wavelet transform have been proposed for power measurements [4-5]. A variety of FFT, DFT and DWT improved algorithms of power measurements have been proposed for the time-varying harmonic in power system [6-7]. These proposed algorithms can evaluate steady state errors for power measurement modules, but cannot evaluate dynamic errors in dynamic load conditions.

Unfortunately, dynamic measurement models, such as PGA unit, power measurement unit and electric energy accumulation unit have not been connected to establish a dynamic energy measurement model for estimating dynamic error in dynamic load condition.

In this paper, we analyse the typical run lengths of the high-speed railway current, and then establish the dynamic model of every smart meter unit. After that, by simulation, the influence of the dynamic current signal fluctuation on the dynamic error of smart meter is analysed based on the dynamic models. Finally, through OOK dynamic test signal, experiments are given to verify simulation results.

II. ANALYSIS OF DYNAMIC LOAD FLUCTUATION OF HIGH-SPEED RAILWAY

The high-speed train in railway transportation is one of the most typical dynamic loads in power grids. In this paper, we select the high speed railway as a typical dynamic load and have sampled instantaneous voltage and current signals at CT and PT secondary part of high voltage metering point. By short time FFT, the amplitude of the voltage and current signals are presented in Fig. 1.

Defining run lengths as a main characteristics to reflect the fast fluctuation of dynamic load signals, run lengths are divided into transient run length (1~8 fundamental period), short-time run length (8~64 fundamental period) and long-time run length (64~512 fundamental period) to reflect the speed of the signal fluctuation.

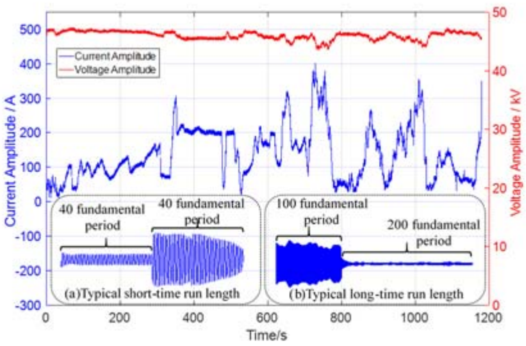

Fig.1 Amplitude time-varying characteristics of high-speed railway instantaneous voltage and current

From Fig.1, we can give following conclusion: (1) the random fluctuation range of the load voltage amplitude is small and the relative value is 8.3%, and voltage has an approximate steady state characteristic. (2) The current amplitude has a large fluctuation range with a relative value 97% and the fluctuation show up fast and random characteristics. (3) the instantaneous current signal has various run length among which the short-time and long-time run length are the main run length, e.g. short-time run length (40:40) and long-time run length (100:200) which are shown in (a) and (b) of Fig. 1 respectively.

III. ESTABLISHMENT OF DYNAMIC ENERFY MEASUREMENT MODEL FOR SMART METER

According to the working mechanism of smart meter, the measurement part of smart meter consists of four parts, including a signal pre-processing unit, a signal conversion unit, an active power measuring unit and an electric energy accumulation unit. They are shown in Fig.2.

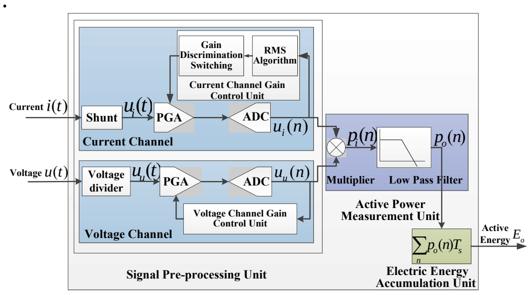

Fig.2 Dynamic energy measurement model of smart meter

The dynamic measurement mathematical models of every part are established separately as follows.

A. Signal pre-processing unit mathematical model

In Fig.2, the amplitude ranges of current signal $i(t)$ and voltage signal $u(t)$ are converted into the limit amplitude $V_m = 700mV$ of the A/D converter input by shunt and voltage divider in the pre-processing unit. And it is ensured that 1.2 times of the maximum peak input is still in the A/D measurement amplitude range so it is needed that $K_m = 0.8V_m$. The mathematical models between the input and output of the smart meter shunt and the voltage divider are established.

Shunt: $$u_i(t) = \frac{K_m}{K^i_{max}} \times i(t) \quad (1)$$

Voltage Divider: $$u_u(t) = \frac{K_m}{K^u_{max}} \times u(t) \quad (2)$$

where $K^i_{max} = \max|i(t)|$ and $K^u_{max} = \max|u(t)|$ are the maximum current $i(t)$ and maximum voltage $u(t)$ respectively, $u_i(t)$ and $u_u(t)$ are the output signals for the shunt and the voltage divider respectively.

B. Signal conversion unit mathematical model

In Fig.2, the signal conversion unit performs PGA amplification and A/D sampling processing on the current signal $u_i(t)$ and the voltage signal $u_u(t)$ which are output by the signal pre-processing unit. Then discrete current signals $u_i(n)$ and discrete voltage signals $u_u(n)$ are output from the signal conversion unit.

a. Mathematical model of current channel gain control unit.

The current gain control unit includes a discrete current RMS algorithm and a gain discrimination switching algorithm.

According to RMS calculation theory based on discrete current signals, in every fundamental period, as for the input discrete current signal $u_i(n)$ with a sampling interval T_s, a RMS value $V_{Irms}(n)$ is calculated from the RMS algorithm unit based on the definition of the RMS value. So that a RMS value $V_{Irms}(n)$ is calculated by current signals $u_i(n)$ within N_T (number of sampling points per fundamental period) discrete times. Obviously, the time interval of $V_{Irms}(n)$ is $N_T T_s$, and the RMS algorithm unit belongs to the multi-sampling rate signal processing system. So, the mathematical model of current RMS measurement algorithm of N_T extraction is established based on the multi-sampling rate signal extraction method.

$$V^2_{Irms}(n) = \sum_{k=0}^{N_T - 1} h_I(k) u_i(N_T n - k) \quad (3)$$

where $\{h_I(k) = 1/N_T : 0 \le k \le N_T - 1\}$ represents current RMS measurement filter. $n \in \mathbb{N}$. $V_{Irms}(n)$ is the current RMS value of the n th fundamental period.

According to the mechanism of current range control of smart meter, within the $M(\in \mathbb{N})$ consecutive fundamental periods, when $V_{Irms}(n)$ is less than the threshold voltage V_{th}, the PGA gain is switched to K_1. When $V_{Irms}(n)$ is larger than the threshold voltage V_{th}, the PGA gain is switched to K_2. It shows that the PGA gain switching has a hysteresis effect of M fundamental periods. According to the working mechanism of gain discrimination hysteresis, the constraint mathematical model of gain hysteresis of PGA gain discrimination switching mechanism can be established.

$$A_i(n)=\begin{cases}\mathrm{K}_1, & \text{s.t. } \max\{V_{Irms}(n)\,|\,n_1\text{-M+1}\le n\le n_1\}<\mathrm{V}_{th}\\ \mathrm{K}_2, & \text{s.t. } \min\{V_{Irms}(n)\,|\,n_2\text{-M+1}\le n\le n_2\}>\mathrm{V}_{th}\\ A_i(n-1), & \text{others}\end{cases} \quad (4)$$

where $A_i(n)$ is the dynamic gain of the n th fundamental period of the current signal $u_i(t)$ .Gain value satisfies $\mathrm{K}_1>\mathrm{K}_2$. M is the number of fundamental periods of PGA gain hysteresis. $n, n_1, n_2 \in \mathbb{N}$.

In the actual power grid of dynamic load conditions, the fluctuation range of the AC voltage amplitude at the power load measurement point is small. Therefore, the PGA of the voltage channel in the smart meter generally adopts a single range operation mode, so the PGA gain is a constant K_u . The voltage channel PGA gain model is

$$A_u(n)=\mathrm{K}_u \quad (5)$$

where $A_u(n)$ is the dynamic gain of the n th fundamental period of the voltage signal $u_u(t)$. $n \in \mathbb{N}$.

b. Mathematical model of current channel and voltage channel input and output.

In the gain control unit of the current channel, the effective value $V_{Irms}(n)$ of the current signal is calculated using the current signal $u_i(n)$ by the "effective value algorithm", and then the current channel PGA gain $A_i(n)$ switching is controlled by the "gain discrimination switching algorithm". The PGA of voltage uses a gain of constant $A_u(n)=\mathrm{K}_u$. The mathematical model of input and output dynamic gain of current channel and voltage channel are established respectively.

Current channel: $$u_i(n)=\sum_{n=0}^{\infty}A_i(\lfloor \tfrac{n}{\mathrm{N_T}}\rfloor)u_i(t)\delta(t-nT_s) \quad (6)$$

Voltage channel: $$u_u(n)=\sum_{n=0}^{\infty}A_u(\lfloor \tfrac{n}{\mathrm{N_T}}\rfloor)u_u(t)\delta(t-nT_s) \quad (7)$$

where $n \in \mathbb{N}$ represents signal sampling discrete moment. $\delta(t-n)$ is unit sampling function. $A_i(\lfloor \frac{n}{\mathrm{N_T}}\rfloor)$ and $A_u(\lfloor \frac{n}{\mathrm{N_T}}\rfloor)$ are dynamic gain of the current and voltage respectively. $\lfloor\bullet\rfloor$ represents round downwards the value to the nearest integer. N_{T} represents number of samples in each fundamental period of the signal. T_s is the sampling interval.

C. *Mathematical model of active power and electric energy accumulation unit*

According to working mechanism of active power measurement unit, instantaneous power signals $p_i(n)$ are obtained by multiplying the discrete current signal $u_i(n)$ and the discrete voltage signal $u_u(n)$ in the active power measuring unit. With the input signals $p_i(n)$ for low pass filter, we can get instantaneous active power signals $p_o(n)$ as output signals. This paper sets $\{h_p(k)=1/\mathrm{L}:0\le k\le \mathrm{L}-1\}$ as the sampled response of the active power low pass filter. According to the input and output relationship of the discrete digital system, the mathematical model of the active power measurement unit convolution operation can be established as follows.

$$p_o(n)=\sum_{k=0}^{\mathrm{L}-1}\{u_u(n)u_i(n)\}*h_p(n)=\sum_{k=0}^{\mathrm{L}-1}p_i(n)*h_p(n) \quad (8)$$

where $n \in \mathbb{N}$ and $\mathrm{L} \in \mathbb{N}$, L represents filter length.

In the smart meter measuring unit, within the input signal measurement time $[0\sim(N_p-1)]$, $N_p \in \mathbb{N}$, the active energy $E_o(N_p)$ can be calculated by the cumulative summation of the multiplication of the instantaneous power signal $p_o(n)$ and sampling interval T_s as follows

$$E_o(\mathrm{N}_p)=\sum_{k=0}^{\mathrm{N}_p+\mathrm{L}-2}p_o(k)T_s \quad (9)$$

where $E_o(N_p)$ means active energy output from the smart meter. T_s is the sampling interval.

IV. SIMULATION ANALYSIS AND EXPERIMENTAL VERIFICATION

We have established the dynamic model of smart meter in part III. And we use high speed railway current with two typical run lengths ((a) the short-time run length and (b) the long-time run length in Fig.1) and actual voltage as the input test signal of the model to analyse the influence of fast fluctuation of dynamic current on dynamic error of smart meter. Then the active energy $E_o(N_p)$ of smart meter is obtained by simulation.

According to the definition of electric energy, the reference electric energy value during the measurement time $[0\sim(N_p-1)]$ is

$$E_s(\mathrm{N}_p)=\sum_{n=0}^{\mathrm{N}_p-1}i(n)u(n)T_s \quad (10)$$

where $i(n)=\sum_{n=0}^{\infty}i(t)\delta(t-n)$ represents discrete current signal. $u(n)=\sum_{n=0}^{\infty}u(t)\delta(t-n)$ represents discrete voltage signal. T_s is the sampling interval. $N_p \in \mathbb{N}$.

The dynamic error δ of the smart meter can be calculated as follows.

$$\delta=\frac{E_o(\mathrm{N}_p)-E_s(\mathrm{N}_p)}{E_s(\mathrm{N}_p)}\times 100\% \quad (11)$$

In the process of simulation analysis, according to the actual application of smart meter, the PGA of current channel generally uses the gain K_1=4, K_2=1 and the delayed fundamental period $M=6$. The PGA gain of voltage channel is K_u=1. In the case of PGA delay and no delay of smart meter, we use short-time run length (40:40) and long-time run length (100:200) of high speed railway current in Fig.1 as input signal to calculate the dynamic errors. They are shown in Table.1.

Table 1 Dynamic errors of typical run lengths of high-speed railway current of smart meter

high speed railway current run lengths	dynamic error (%)	
	PGA delay (M=6)	PGA no delay
short-time run length (40:40)	-12.34	6.74×10^{-6}
long-time run length(100:200)	-4.21	4.41×10^{-6}

From the Table.1 we know that the hysteresis response of the PGA is the main cause of dynamic error of smart meter. Moreover, the dynamic error of the short-time run length is larger than the long-time run length.

The results of simulation are verified by experiment with smart meter dynamic error test device HE5020 (the device has been tested and verified at the National Institute of Metrology) in [8]. OOK dynamic test signal in [8] is used as the experimental test current signal (two typical run lengths with different on-off ratios (40:40 and 100:200), same as the simulation test signal). Experimental test conditions are shown in Table.2.

Table 2 Dynamic error experimental test conditions

dynamic error test device of smart meter	model：HE5020 rated voltage：57.7/100V rated current：5A
standard energy meter	thunderbolt：RD-33 meter constant：0.0001Wh/P
test stimulus signal	OOK dynamic test current signal standard sine wave voltage signal
measured electric meter	smart electricity meter

The dynamic error results of the experimental test are shown in Table 3. For the convenience of analysis and comparison, the dynamic error results of the simulation analysis (in Table.1) are also listed in Table.3.

Table 3 Dynamic errors of experimental test and simulation analysis

high speed railway current/OOK on-off ratios period length	dynamic error (%)	
	simulation analysis	experiment test
short-time run length(40:40)	-12.34	-14.73
long-time run length （100:200）	-4.21	-4.84

In the Table.3, it is shown that the experimental results are consistent with the results of simulation analysis, indicating that the method for establishing the dynamic model of the smart meter is right.

V. CONCLUSIONS

In this paper, the fast fluctuation of high-speed railway current has been analysed. And dynamic models of every unit in smart meter have been established. The dynamic error of two typical run lengths of dynamic current has been simulated in the model. The simulation results have been verified by experiment with OOK dynamic test current signal.

Summarizing the above simulation and experiment, we can obtain the results as follows. (1) The dynamic energy measurement model of smart meter can be used to estimate the dynamic error in the fast fluctuation of dynamic current condition. (2) The gain feedback switching of PGA unit causes the current signal clipping, which is the main source of the dynamic error of the smart meter. (3) The short-time run length of dynamic current has greater impact on the dynamic error of smart meter than the long-time run length.

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