

The Whole-system Model of Smart Electricity Meter

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Abstract – In order to analyze the error effect of smart electricity meter under different dynamic load current fluctuation and evaluate the errors of smart electricity meter. At first, the models of four units in smart electricity meter are established based on their mechanism, which include voltage channel model, current channel model with a programmable gain amplifier (PGA), active power measurement model and energy measurement model. Secondly, the whole-system model of smart electricity meter is established base on above four models to reflect the inside ralations causing dynamic errors. Finally, a dynamic error testing system is built to test the dynamic errors of the typical electricity meter, and the correctness of the whole-system model is verified by comparing the measured dynamic errors and simulation errors. The result shows that the whole-system model can be used to evaluate the errors affected by the complicated load current fluctuation.

Keywords –smart electricity meter, whole-system model, dynamic load, dynamic error

I. INTRODUCTION

With the increasing use of the intermittent energy and nonlinear dynamic loads in smart grid, the electrical loads in power systems have shown some dynamic characteristics[1-3]. Under this dynamic load conditions, many currently used smart electricity meters (hereinafter referred to as smart meters) can't meet the measurement requirements and even have serious dynamic errors in energy metering. These phenomenon lead to the unfairness of electric energy transaction between the power supplier and the user.

In order to analyze the dynamic error of smart meters, researchers worldwide have begun to research into the above problems and established some dynamic models of smart electricity meter in recent years. For the energy meter input amplifier, the range effect of the programmable gain amplifier (PGA) of the input channel has been studied and the steady-state errors of the amplifier have been improved [4]. For the power measurement unit, the influence of frequency offset on

the power measurement error has been analyzed, and a new weighting algorithm to reduce this effect has been proposed [5]. A microprocessor based on fast real power measurement device has been developed to demonstrate its capability in measured active power in balanced and various unbalanced conditions [6]. For the energy measurement unit, a bidirectional energy measurement algorithm based on fundamental component extraction and AC sampling have been given [7].

The above researches have significantly influenced the steady-state error measurment accuracy of smart electricity meter. Unfortunately, it is difficult to generate dynamic test signal to compeletly reflect the actual complicated dynamic load current fluctuation. Moreover, the errors affected by these complicated loads can not be measured through the traditional dynamic error testing system of smart electricity meters. So, it is a channlege to establish a model for evaluating the dynamic errors affected by the complicated load current fluctuation.

Aiming at the above problems, we are motivated to establish the whole-system model based on the model of four main units in smart electricity meter. After that, a dynamic error test system is built to verify the correctness of the whole-system model, which can be used to make clear the dynamic error effect of dynamic load with different current fluctuation characteristic.

II. DYNAMIC MODEL OF SMART ELECTRICITY METER

A. System block diagram of electric energy meter

The metering module of the meter in Fig.1 contains four units: (1) voltage channel consisted of PGA (programmable gain amplifier) with fixed gain and ADC (analog to digital conversion); (2) current channel, including PGA with changeable gain, PGA gain feedback control and ADC parts; (3) active power measurement unit made of multiplier and lower filter; (4) electric energy measurement unit. After amplification with various gains through PGA and sampling by ADC, voltage signal $u_s(t)$ and current signal $i_s(t)$ become discrete signals $u(n)$ and $i(n)$ respectively. Next, the instantaneous power signal $p(n)$ multiplied by $u(n)$

and $i(n)$ is processed into instantaneous active power signal $p_o(n)$ after filtering the AC component of $p_o(n)$ through the low-pass filter. Finally, the energy signal $e_o(n)$ is obtained by accumulating $p_o(n)$ during measurement time which is controlled by "Power Accumulation Algorithm".

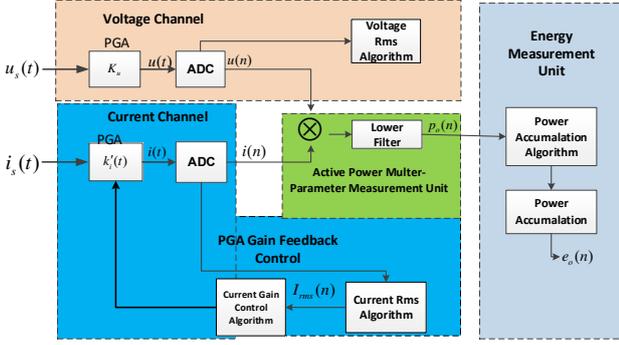


Fig. 1. Physical model of electricity metering module

B. Mathematical models of Voltage Channel

In actual power grid, the amplitude of AC voltage has small fluctuation range in the power load metering port under the dynamic load conditions and a voltage gain K_u is set to constant in the voltage PGA. The mathematical model of this part can be described as

$$u(n) = \sum_{n=0}^{\infty} \delta(t - nT_s) u(t) = \sum_{n=0}^{\infty} \delta(t - nT_s) K_u u_s(t) \quad (1)$$

where n, T_s represent the sampling point and interval of ADC respectively.

C. Mathematical model of Current Channel including feedback control

Different from voltage signal, the current RMS value changes in an extensive range under dynamic load conditions but it does not change much within one period. Thus, the algorithm to calculate the dynamic current RMS value $\tilde{I}_{rms}(n')$ is

$$I_{rms}(n') = I_{rms}(N_T n) = \sqrt{\frac{1}{N_T} \sum_{k=0}^{N_T-1} i^2(N_T n' - k)} \Big|_{n' = \lfloor \frac{n}{N_T} \rfloor} \quad (2)$$

where N_T is the sampling points during a fundamental period.

In the current PGA of smart meter, double gains K_{i1} and K_{i2} ($K_{i1} < K_{i2}$) are set in amplifier circuit. The principle of current gain control is shown in Fig. 2. I_{th} is the current threshold, when $\tilde{I}_{rms}(n')$ changes from below I_{th} to above I_{th} , the current gain is changed to K_{i1} from K_{i2} after M fundamental periods rather than changing immediately. Similarly, when $\tilde{I}_{rms}(n')$ changes reversely, the current gain's change is contrary to the former. In general, due to the current gain is changed

after M fundamental periods rather than changing immediately. $\tilde{I}_{rms}(n')$ is amplified inappropriately since feedback lag effect of the PGA range switching, which causes dynamic error in the current channel inevitably. The larger the value M or the more frequent the current value fluctuates, the greater the difference between the current channel output signal and the actual current input signal is, and the greater the active power and energy metering error caused by this. On the contrary, the value is too small, which may cause periodic interference.

By considering the equation (2) and the control principle of current PGA gain, the PGA gain control algorithm of n' th period can be determined as:

$$\tilde{k}_i(n') = \begin{cases} K_{i1}, \min\{\tilde{I}_{rms}(n') : n' = n'_1, n'_1-1, \dots, n'_1-M+1\} > I_{th} \\ K_{i2}, \max\{\tilde{I}_{rms}(n') : n' = n'_2, n'_2-1, \dots, n'_2-M+1\} \leq I_{th} \end{cases} \quad (3)$$

As the instantaneous gain value $k_i(n)$ keeps constant in different time during each period, we set $k_i(n) = \tilde{k}_i(n') \Big|_{n' = \lfloor \frac{n}{N_T} \rfloor}$, where $\lfloor \cdot \rfloor$ represents round downwards the value to the nearest integer. Together with equations (2) and (3), the mathematical model of current channel including feedback control can be expressed as

$$i(n) = \sum_{n=0}^{\infty} \delta(t - nT_s) i_s(t) \tilde{k}_i(n') \Big|_{n' = \lfloor \frac{n}{N_T} \rfloor} \quad (4)$$

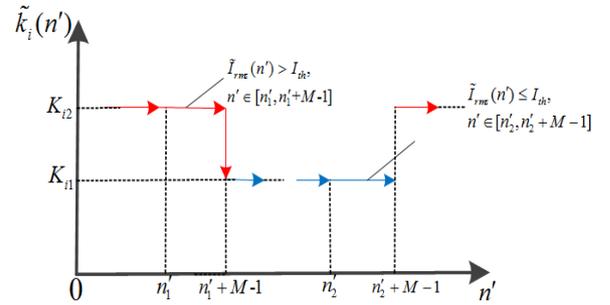


Fig. 2. Control principle of PGA gain

D. Dynamic Model of Active Power Measurement Unit

In Fig.1, the discrete-time sequences $u(n), i(n), p(n)$ and $p_o(n)$ during measured time can be separately mapped as a vector in n -dimensional Euclidean space R^n

$$\mathbf{U}_q = [u(n), u(n-1), \dots, u(n-q+1)]^T \quad (5)$$

$$\mathbf{I}_q = [i(n), i(n-1), \dots, i(n-q+1)]^T \quad (6)$$

$$\mathbf{\tilde{P}}_m = [p_o(n-1), p_o(n-2), \dots, p_o(n-m)]^T \quad (7)$$

$$\mathbf{P}_q = [p(n), p(n-1), \dots, p(n-q+1)]^T \quad (8)$$

Note that, $p(n)$ is a causal sequence and $p(n) = 0$ when $n < 0$.

According to the properties of Linear Shift-Invariant

(LSI) system, the output of the active power measurement unit $p_o(n)$ can be expressed as a linear combination of q -dimensional ($q \in N$) input vector \mathbf{P}_q and m -dimensional ($m \in N$) output vector $\tilde{\mathbf{P}}_m$

$$p_o(n) = -\mathbf{A}\tilde{\mathbf{P}}_m + \mathbf{B}\mathbf{P}_q \quad (9)$$

where the parameter vector $\mathbf{A} = [a_1, a_2, \dots, a_m]$ and $\mathbf{B} = [b_0, b_1, \dots, b_{q-1}]$.

Furthermore, \mathbf{P}_q can be expressed as a hadamard product form of column vectors \mathbf{U}_q and \mathbf{I}_q , that is $\mathbf{P}_q = \mathbf{U}_q \odot \mathbf{I}_q$. Thus, the dynamic model structure of active power measurement unit can be rewritten as:

$$p_o(n) = -\mathbf{A}\tilde{\mathbf{P}}_m + \mathbf{B}[\mathbf{U}_q \odot \mathbf{I}_q] \quad (10)$$

Under the steady conditions, the parameters of the model $\mathbf{A} = 0$, $\mathbf{B} = \mathbf{H} = [h_0, h_1, \dots, h_{N_T-1}]$, $q = N_T$, which indicate that the steady model of active power measurement unit is a FIR filter model with fixed parameters and length. And the value of h_k is determined by specific active power measurement algorithms.

Based on the principle that the steady model is a special form of model analyzed under the dynamic condition, this paper defines the dynamic model of this unit with adjustable filter coefficient and length L as

$$p_o(n) = \mathbf{H}\mathbf{P}_L = \mathbf{H}[\mathbf{U}_L \odot \mathbf{I}_L] \quad (11)$$

where $\mathbf{H} = [h_0, h_1, \dots, h_{L-1}]$.

E. Dynamic Model of Electric Energy Measurement Unit

In this paper, $e_o(n)$ is defined as the accumulation value of the product of the instantaneous active power $p_o(n)$ and the sampling interval T_s during the period $[0 \sim n]$, which represents the active electric energy measured by electric energy meter.

$$e_o(n) = \sum_{k=0}^n g(k) p_o(k) T_s \quad (12)$$

$$g(k) = \begin{cases} 1, & i(k) > I_{qth} \text{ (or } p_o(k) > P_{qth}) \\ 0, & \text{other} \end{cases} \quad (13)$$

where I_{qth} and P_{qth} are the starting threshold, $g(k) = 1$ represents performing electric energy accumulation at this moment, $g(k) = 0$ represents the opposite perform.

The instantaneous active power during the period $[0 \sim n]$ is defined respectively as

$$p_o(k) = \mathbf{H}_L \mathbf{P}_{k,L} = [h_0, h_1, \dots, h_{L-1}] \begin{bmatrix} p(k) \\ p(k-1) \\ \vdots \\ p(k-L+1) \end{bmatrix} \quad (14)$$

where $k \in [0, n]$.

By equations (12) and (14), the dynamic model of the electric energy measurement unit can be expressed as

$$e_o(n) = T_s \sum_{k=0}^n g(k) \mathbf{H}_L \mathbf{P}_{k,L} \quad (15)$$

Equations (15) reflects the corresponding relationship between the active electric energy and the instantaneous active power.

F. The Whole-System Model

Based on the transfer relationship between input signals and output signals described in equations (1), (4), (12) and (14), the whole-system model of the meter is derived as equation (16)

$$e_o(n) = T_s \mathbf{H}_L \begin{bmatrix} p(0) & p(1) & & p(n) \\ 0 & p(0) & \dots & p(n-1) \\ \vdots & \vdots & & \vdots \\ 0 & 0 & & p(n+1-L) \end{bmatrix} \begin{bmatrix} g(0) \\ g(1) \\ \dots \\ g(n) \end{bmatrix} \quad (16)$$

$$= T_s \mathbf{H}_L \begin{bmatrix} \sum_{k=0}^n g(k) K_u \tilde{k}_i(n') u_s(n) i_s(n) \\ \sum_{k=0}^{n-1} g(k+1) K_u \tilde{k}_i(n') u_s(n) i_s(n) \\ \vdots \\ \sum_{k=0}^{n-L+1} g(k+L-1) K_u \tilde{k}_i(n') u_s(n) i_s(n) \end{bmatrix}$$

$$\text{where } n' = \left\lfloor \frac{n}{N_T} \right\rfloor.$$

Above dynamic models described in each unit and the whole-system model indicate that the dynamic error generated in the meter is a comprehensive consequence of current PGA gains, filter coefficients and the power accumulation.

III. RESULTS AND DISCUSSIONS

In order to verify the correctness of the whole-system model, we built a dynamic error test system to test the dynamic errors of the typical electricity meter. As shown in Fig.3, the dynamic error test system includes five parts: computer, program-controlled power supply, standard meter, dynamic error test device and the measured meter. Firstly, the steady-state voltage and current generated by computer-controlled programmable power supply are input into the standard meter to obtain the standard electrical energy E_s . At the same time, the steady-state current is sent into dynamic error test device to generate dynamic current signal. Then, the OOK signal and the steady-state voltage are sent to the measured meter to get the electrical energy E_1 .

Finally, the testing dynamic error ε_1 of the measured meter is shown in the dynamic error test device

$$\varepsilon_1 = \frac{E_1 - E_S}{E_S} \quad (17)$$

The simulated dynamic error ε_2 calculated according to the whole-system simulation model is built in MATLAB.

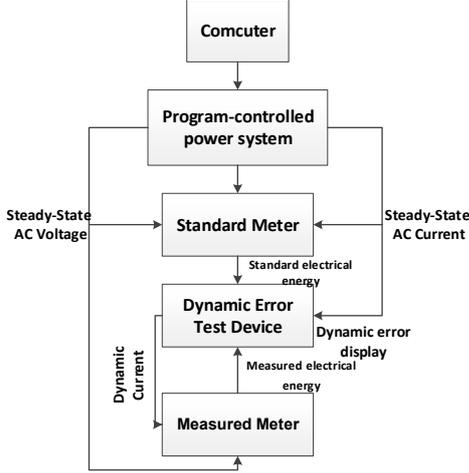


Fig. 3. Testing system of dynamic error

The adopted dynamic current signal of the error test system is the OOK (On-Off-Key) signals that reflect three dynamic modes: transient, short and long mode of dynamic load, proposed in paper [8]. OOK signal is a dynamic error test signal generated by a binary sequence to control a steady state test signal, and the on-off ratio A:B means that A periods are on and B periods are off, which reflect the different current fluctuation of dynamic load. The test results of the testing dynamic error and simulated dynamic errors are shown in Table 1.

Table 1. Comparison between testing dynamic errors and simulated dynamic errors.

On-off ratio A:B	Testing dynamic errors (%)	Simulated dynamic errors (%)
20:100	-57.67	-57.40
30:80	-38.01	-39.14
40:100	-30.61	-29.36
80:200	-16.08	-16.18
300:300	-5.92	-5.35

The results in Table 1 show that under the same test signal excitation, the absolute values of difference between measured dynamic errors and simulated dynamic errors are less than 2%. Therefore, the whole-system model proposed in this paper can replace the measured meter to analyze the dynamic error.

IV. CONCLUSIONS

In this paper, a novel whole-system model of smart electricity meter considering dynamic error has been proposed. The model includes four units as following, the voltage channel unit, the current channel unit with PGA gain feedback control, active power measurement unit and electric energy measurement unit.

Then the correctness of the proposed model has been verified by comparing the dynamic errors which respectively obtained by the actual measured meter and the proposed model. The results indicate that the whole-system model can be used to evaluate the errors affected by the complicated load current fluctuation. Meanwhile, the model has important application value to optimize the overall design of smart electricity meter and to select electric energy meter for power department in dynamic load situation.

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