A New Digital Predistortion Algorithms Scheme of Feedback FIR Cross-Term Memory Polynomial Model for Short-Wave Power Amplifier

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ABSTRACT Due to the non-linear behavior, high fractional bandwidth, relatively poor circuit matching, large standing wave of output port, large fluctuation of power tube temperature of the short-wave power amplifier (PA), it is difficult to achieve the expected performance in HF (High Frequency) communication to maintain high efficiency and improve the linearity of HF power amplifier at the same time. However, there are no optimization measures for the above problems in the traditional digital pre-distortion (DPD) model, which is always recognized as an effective technique to improve system linearity and efficiency. In this paper, the new Feedback FIR Cross-term Memory Polynomial Model (MPM) to compensate the characteristics of the short-wave PA is presented. The experimental results show that, comparing with the traditional MPM DPD look-up table (LUT) method and the Generalized Memory Polynomial Model (GMPM) LUT method, this model can improve IM3 of Adjacent Channels Power Ratio (ACPR) about 10 dB.

INDEX TERMS Short-wave power amplifier, adaptive digital predistorter, power amplifier linearization, memory polynomial model (MPM), look-up table (LUT).

I. INTRODUCTION
Because of strong autonomous communication ability and anti-destructive ability, more and more attention has been paid to shortwave communication in recent years. Realize the signal transmission of hundreds to tens of thousands of kilometers. In addition to having a signal transmission system that can realize hundreds to tens of thousands of kilometers, shortwave communication is also the only remote communication that is not restricted by active relay system and network hub. The short-wave power amplifier (PA) is a non-linear device and critical component in HF (High Frequency) communication, which inevitably leads to cross intermodulation of adjacent signals, in band distortion and out of band spectrum growth. This nonlinearity is the main factor affecting the performance of HF communication. The linear method of PA including digital predistortion (DPD) is widely used in this field [1]–[6].

The application of DPD technology to short-wave communication is facing new problems in improving the linearity and efficiency of short-wave PA. First of all, the performance of the PA is related to the power impedance matching of the power tube. In the wireless cellular mobile communication system, the fractional bandwidth of the PA is relatively small and the matching circuit design is relatively easy. For the short-wave PA, the performance of different frequency points of the power tube in the working frequency range is quite different [7], so it is difficult to take into account the optimal performance of each frequency point.

Secondly, because of the large physical size of the isolator, it is not easy to be integrated. In practical engineering, the HF PA is often directly connected with the antenna through the feeder, and the Voltage Standing Wave Ratio (VSWR) of the antenna port is generally greater than 2.5. The reflected wave is reflected back to the output port of the PA through the coupler, which affects the normal working state of the PA, and the delay of the standing wave reflection path is large, which makes the traditional predistortion model is difficult to fit the standing wave distortion.
FIGURE 1. Memoryless diagram block with LUT.

Thirdly, the main reasons for the electrical memory effect are the irregularity of the frequency response near the carrier frequency, the impedance variation of the bias circuit at the baseband frequency, and the harmonic loading of the PA level.

Finally, the short-time burst application of HF PA results in the increase of power tube temperature and PA temperature fluctuation. At the same time, the unstable leakage voltage of PA results in the great change of PA state at different times, and the nonlinear characteristics also change.

It can be seen from the above analysis that there are some problems in the short-wave PA, such as wide working frequency band, relatively poor circuit matching, large standing wave of output port, large fluctuation of power tube temperature and leakage voltage, while there are no optimization measures for the above problems in the traditional predistortion model. When the traditional predistortion model is applied to the short-wave PA, it is difficult to achieve the expected performance. Therefore, it is a problem to develop a new DPD model.

Based on the memory polynomial model (MPM) [8], this paper proposes a new DPD model of Feedback FIR-Cross-Term MPM for HF PAs, in which the above two compensation model are connected in parallel and is organized as follows. Section II discusses detailed issues about the DPD algorithm and architecture. Section III presents the Feedback FIR Cross-term MPM DPD model for HF PAs. Experimental validation results are shown in Section IV, followed by a brief conclusion in Section V.

II. DPD MODEL BASED ON LOOK-UP TABLE

A. LOOK-UP TABLE PREDISTORTER

DPD with the adaption and updating of LUT has long been recognized as an effective technique to improve system linearity and efficiency by pre-processing the PA input signal to compensate for these unwanted effects [9]–[12]. The use of look-up table (LUT) as a low-cost, viable, fast-adapting predistorter technique is established by the work of Cavers in the 1990s [13].

B. MEMORYLESS MODEL BASED ON LUT

The basic memoryless approach is to use a complex gain-based LUT to approximate the inverse of the AM to AM (gain) and AM to PM (phase) characteristics of PA. The LUT is a memoryless model that describes a nonlinear system used in the form of complex gain response for different input powers as shown in Figure 1.

FIGURE 2. Memory diagram block with LUT.

\[ P(x(n)) \] refers to the instant power calculation of \( x(n) \) and serves as the address index of LUT (\( P(x(n)) \)) which contains the polynomial coefficients. Therefore, the instant output signal \( z(n) \) of memoryless DPD model is obtained as follows:

\[ z(n) = x(n) \ast LUT(P(x(n))) \]  

C. MPM BASED ON LUT

For predistortion of PA with memory effect, the methods of multiple LUT are proposed [14], [15].

If the output \( z(n) \) at time \( n \) is related to the present and up to \( Q \) previous input samples, DPD model is referred to memory model. As a classical memory model, which is shown in Figure 2, MPM can be expressed as Equation (2).

\[ z(n) = \sum_{k=0}^{K-1} \sum_{q=0}^{Q} a_{k,q} |x(n-q)| |x(n-q)|^k \]  

As shown in Figure 2, \( LUT_q(|x(n-q)|) \) means a LUT containing the corresponding polynomial coefficients for delay \( q \). And \( x(n-q) \) acts as the address index of the LUT.

The \( a_{k,q} \) represents the \( k^{th} \) polynomial order and the \( q^{th} \) memory depth (time delay). Because the odd-order terms generate only odd-order harmonic and intermodulation, while even-order terms produce only even-order harmonic and intermodulation. Equation (2) is simplified as follows:

\[ z(n) = \sum_{q=0}^{Q} x(n-q) \]

\[ \times \sum_{k=1}^{K/2} a_{k,q} |x(n-q)|^{2k} (K = \text{even}) \]

\[ z(n) = \sum_{q=0}^{Q} x(n-q) \]

\[ \times \sum_{k=1}^{(K-1)/2} a_{k,q} |x(n-q)|^{2k} (K = \text{odd}) \]

Define \( LUT_q(|x(n-q)|) = \sum_{k=0}^{K} a_{k,q} |x(n-q)|^{2k} \), we obtain

\[ z(n) = \sum_{q=0}^{Q} x(n-q) LUT_q(|x(n-q)|) \]  

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Several variations of the MPM have been proposed in the literature. These include the orthogonal memory polynomial model, the memory polynomial model with cross-terms also referred to as the generalized memory polynomial model (GMPM) [16], [17].

III. FEEDBACK FIR-CROSS-TERM MPM DPD MODEL

The key part of the DPD model extraction process is how to find the model with the highest degree of conformity with signal mode and PA characteristics, and then calculate predistortion parameters. The anti-model of the predistortion model, the main requirements for the predistortion model are:

1) Effectiveness, which means the model can effectively describe the distortion characteristics of PA;
2) Universality, which means the model can be applied to the distortion characteristics of most types of PAs.
3) Realizability, which means model overhead should be controlled within a certain range and multi-dimensional index tables should be avoided as far as possible.

As previously analyzed, there are some problems in the short-wave PA, such as wide working frequency band, relatively poor circuit matching, large standing wave of output port, large fluctuation of power tube temperature and leakage voltage, while it is not enough to use MPM model, Hammerstein model and Wiener model alone to compensate the characteristics of the short-wave PA.

According to the characteristics of short-wave PA, the improvement we proposed for traditional DPD model and its application should include the following aspects:

1) a FIR Cross-term MPM is introduced to represent the thermal memory of power tube;
2) Based on that, further consideration should be given to the relatively big fractional bandwidth of the short-wave PA, a Feedback DPD model is proposed to take into account the optimal performance of each frequency point of the power tube in the working frequency range;
3) The model of standing wave compensation is introduced to improve the predistortion performance in the case of large standing wave.

A. FIR CROSS-TERM MPM MODEL

Considering the requirements for eliminating intermodulation distortion caused by the thermal memory of power tube, by integrating FIR weak non-linear filters (shown as Figure 3), a FIR cross-term MPM is designed to overcome the memory effect, which is shown in Figure 4.

The output signal \( \text{FIR} (n) \) is obtained as follows:

\[
\text{FIR} (x) = \sum_{i=0}^{M} a_i x (n - i)
\]

The output signal \( z(n) \) of new FIR-MPM DPD model is obtained as follows:

\[
z(n) = x(n) \left[ LUT_{1,1} (\text{FIR} (x (n)) + LUT_{1,2} (x (n))
\]

B. FEEDBACK DPD MODEL

Different from the traditional DPD model, the delay output signal is used as the feedback information in the expression of the model. Hence, the interaction between the feedback lag output signal and the input signal is further considered in the new model, which is shown in Figure 5.

The output signal \( z(n) \) of new Feedback DPD model is obtained as follows:

\[
z(n) = \sum_{q_1=3}^{Q_1} x(n - q_1) LUT_{1,q_1} (|x (n - q_1)|)
\]

C. VSWR COMPENSATION MODEL

The VSWR compensation model includes a large dynamic variable delay unit and a complex FIR filter. The large dynamic variable delay unit delays the input baseband complex signal \( x(n) \), and the delay result is output to the complex FIR filter, which filters the delayed baseband complex
signal and generates the standing wave compensation component \( v(n) \).

After the delay alignment, the nonlinear compensation component of \( x(n) \) and \( v(n) \) are added to obtain the intermediate output result of predistortion \( z(n) \).

\[
v(n) = \sum_{q_3=1}^{Q_3} b_{q_3} x(n - q_3)
\]

Therefore, we propose the Feedback FIR Cross-term MPM DPD model, which is shown as Figure 6. In this model, we integrate the feedback structure combining with the FIR Cross-term MPM model for representing the thermal memory of power tube and the FIR structure for representing standing-wave ratio compensation.

As shown in Figure 6, the output signal \( z(n) \) of new Feedback FIR Cross-term MPM DPD model is obtained as follows:

\[
z(n) = x(n) \left[ LUT_{1,1} \sum_{i=0}^{M} a_i x(n - i) + LUT_{1,2} (x(n)) + LUT_{1,3} (x(n - 1)) \right] + \sum_{q_1=1}^{Q_1} x(n - q_1) LUT_{1,q_1} (|x(n - q_1)|) + \sum_{q_2=1}^{Q_2} z(n - q_2) LUT \_2,q_2 (|x(n)|) + \sum_{q_3=1}^{Q_3} b_{q_3} x(n - q_3)
\]

(7)

in which,

\[
LUT_{1}(x(n)) = \sum_{k_1=1}^{K_1} a_{k_1} |x(n)|^{k_1}
\]

(8)

\[
LUT_{2}(x(n)) = \sum_{k_2=0}^{K_2} b_{k_2} |x(n)|^{k_2}
\]

(9)

In Equation (8), the \( LUT_1 \) is used to build the polynomial system, and the address of the \( LUT_1 \) is \( |x(n)| \). Assuming that the total number of coefficients in this \( LUT_1 \) is 128, \( \sum_{k_1=1}^{K_1} a_{k_1} |m\Delta|^{k_1} \) is the content of the \( LUT_1 \), where \( \Delta = \frac{1}{128} \); \( m = 1, 2, 3, \ldots, 128 \).

The storage content and specific structure of \( LUT_1 \) are shown in Figure 7.

In Equation (9), the \( LUT_2 \) is used to build the polynomial system, and the address of the \( LUT_2 \) is \( |x(n)| \). Assuming that the total number of cells in this \( LUT_2 \) is 128, \( \sum_{k_2=0}^{K_2} b_{k_2} |m\Delta|^{k_2} \) is the content of the \( LUT_2 \), where \( \Delta = \frac{1}{128} \); \( m = 1, 2, 3, \ldots, 128 \).

The storage content and specific structure of \( LUT_2 \) are shown in Figure 8.

When the \( LUT_1 \) and \( LUT_2 \) are updated, the coefficient estimation module calculates the required storage content, and then writes the storage content to the \( LUT_1 \) and \( LUT_2 \) according to the address, so as to complete the update of \( LUT_1 \) and \( LUT_2 \).

Adaptive algorithm of recursive least squares (RLS) is an algorithm which starts from an initial point and adjusts the coefficients dynamically according to newly sampled input and output. Once initial value is properly set, the coefficients always converge to stable states. RLS is also applicable for both equation-error method and output-error method. As a result, we choose RLS used for coefficient estimation module to extract the coefficients of Equation (7).
Rewriting Equation (7) in a matrix form:

\[ z(n) = w^T u(n), \]  

where \( w \) are the coefficients and \( u(n) \) are polynomials of inputs and outputs. Omitting the tedious and complicated mathematical derivation the final RLS procedure is

\[ \epsilon(n) = z(n) - u^T(n)w(n - 1) \]  

\[ w(n) = w(n - 1) + k(n)\epsilon^*(n) \]  

\[ k(n) = \frac{P(n - 1)u^*(n)}{1 + u^T(n)P(n - 1)u^*(n)} \]  

\[ P(n) = P(n - 1) - k(n)u^T(n)P(n - 1) \]

IV. EXPERIMENTAL DESIGN

In order to verify the DPD effect of HF PA, the AB class HF PA with a central frequency of 1.6\( \sim \)30 MHz and a power output of 125 W are used to test, as shown in Figure 9.

According to the test standard of HF system, the two-tone signal with an interval of 24KHz is used as the test verification signal. We also can see that the maximum allowable levels of noise and distortion as a function of the frequency offset in Figure 10(a). From Figure 10(b)-(d) it is observed that comparing with the traditional MPM DPD LUT method (\( k = 7, Q = 5 \)), and the GMPM DPD LUT method (\( k = 7, Q = 5 \)), the new Feedback FIR Cross-Term MPM (\( k = 5, Q = 3, Q_1 = 5, Q_3 = 7, Q_3 = 25 \)) we mentioned can improve the IM3 of ACPR from more than 10dB.

The AM–AM and AM–PM performance of MPM comparing with this work is shown in Figure 11.

The normalized mean-squared error (NMSE) [18], defined by the Equation. (15), is used to validate the performance of DPD with this work.

\[ \text{NMSE}_{\text{dB}} = 10 \log_{10} \left( \frac{\sum_{n=1}^{N} |z(n) - \tilde{z}(n)|^2}{\sum_{n=1}^{N} |z(n)|^2} \right), \]  

where \( \tilde{z}(n) \) is the simulated output and \( z(n) \) is the desired output. The results are reported in Table 1.
TABLE 1. Accuracy and IM3 of ACPR using different method.

| Method                  | NMSE       | ACLRLower/ACLRUpper       |
|-------------------------|------------|---------------------------|
| Without DPD             | -34.31dB   | -16.26dB/-16.05dB         |
| DPD with MPM (K=7, Q=5) | -47.26dB   | -41.48dB/-45.26dB         |
| DPD with GMPM (K=5, Q=5)| -49.64dB   | -44.90dB/-49.37dB         |
| Feedback FIR Cross-term MPM DPD model | -54.18dB   | -53.03dB/-56.17dB         |

FIGURE 11. AM-AM and AM-PM of PA output with and without proposed DPD solution.

V. CONCLUSION

We present the Feedback FIR Cross-term MPM DPD model to overcome the non-linear behavior, high fractional bandwidth, relatively poor circuit matching, large standing wave of output port and large fluctuation of power tube temperature of the short-wave PA in this paper. Therefore, comparing with the MPM and GMPM DPD LUT method, the DPD performance in HF system is improved about 10dB for HF PA’s output signal, compensate for short-wave PA nonlinear distortion, and improve the short-wave radio communication quality effectively.

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