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# ORDER REDUCTION OF AIR CORE TRANSFORMER USING CONTINUED FRACTION

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**Abstract**

In this manuscript, the higher-order transfer function of an air core linear section electrical transformer is presented. The higher-order system is reduced using the Cauer 3rd form of Continued Fraction. This technique has its own advantages and shortcomings in the model order reduction field. The effective, efficient and comparative analysis of the derived reduced order form is done and discussed using step response parameters (such as settling time, rise time, peak time and peak value). The Original higher order transfer function of the Air Core Transformer is reduced using a continued fraction and obtained second order is also compared with second-order available in literature the performance indices Integral Square Error (ISE), Integral Absolute Error (IAE) and Integral Time-Weighted Absolute Error (ITAE) also computed and compared.

Keywords: Air-core transformer, Cauer 3rd form, Continued fraction (C.F.), Linear-section, Integral absolute error (IAE), Integral square error (ISE), Integral time-weighted absolute error (ITAE), Model order reduction (MOR).

## 1. Introduction

Modern mathematics has the power to decipher complications in the field of engineering. The calculation and understanding of Original Higher Order (OHO) systems using procedures and methods become complex as the order rise. It is also an annoying and time-consuming task to understand the OHO system. Converting the tedious task into butter bite and examination the structure easily is reasonable to transform the OHO system into ROMs. The process of conversion from OHO system to ROMs either by conventionally or applying optimization techniques, the lower-order model comes out to have the same type, comparable and/or some time better response [1].

In recent years, the cutting-edge technology in power system engineering has developed many devices, including a static device, which performs its duty with high efficiency. The Air-core Transformer is a static device, which has a higher-order transfer function. It is not stress-free to appreciate the design of the transformer and in order to study and to understand; lower order of a detailed linear transformer model needs to study by those methods which systematically reduce the OHO system and have the same basic property as of the higher-order. The Air-core Transformers have advanced technology. The steady-state model of the air-core transformers is presented in phasor form using an equivalent circuit. The transfer function model of it may be expressed in the time domain and frequency domain for order reduction.

In the field of MOR, numerous methods in control engineering have been developed for ROMs. Some well-established methods are moment matching [1, 2], stability equation [3-6], continued fraction method has three sub-divisions known as Cauer 1$^{st}$, Cauer 2$^{nd}$ form and by intermixing first two methods (Cauer 1$^{st}$ and Cauer 2$^{nd}$ form), i.e., Cauer 3$^{rd}$ form has presented in [7]. The other traditional methods as Pade approximation [8], Routh approximation [9], Routh stability criteria [10-14], Error minimization techniques [15] are available in the literature. In moment matching, the OHO system dynamics match its lower moments and property of destabilizing the stabilized system and vice-versa. However, the stability equation (SE) gives guaranteed the stable reduced order of a system. In Cauer 1$^{st}$ form, the steady-state error is originating. In a mandate to escape the steady state, the reduced order numerator is again multiplied by a constant in Cauer 1$^{st}$ form. However, the Cauer 2$^{nd}$ form provides a better-reduced result as compared to the Cauer 1$^{st}$ form.

In the decade of 70s, the concepts of hybrid methods in the field of model order reduction were explored. This technique is applied for reduction using two different methods. Shieh and Goldman [16] suggested the miscellaneous Cauer form for linear system reduction, as applied by Shieh and Wei [17, 18], although the idea of a mixed technique for multivariable system reduction and the concept of dominant-pole and Continued Fraction with some inputs-output are given and in which, used to get the ROMs.

The computational techniques used for reduction are fast, hectic-free and free from the calculation and give better results. The optimization based methods available in literature are Cuckoo Search Algorithm (CSA) [19], Particle Swarm Optimization (PSO) [20], Artificial Bee Colony (ABC), Genetic Algorithm (GA), Simulated Annealing (SA) [20], Bat Algorithm (BA) [21], these respond frequently and calculation cycle may take few days to weeks for results.

The organization of the article is allocated to mainly six sections. The problem declaration is defined in Section 2, Section 3 pronounces the scheme of a method, and Section 4 gives the problem construction. Section 5 gives the details of result analysis and comparisons of decreased order with the decreased order available in the literature and last Section 6 is of a conclusion followed by a reference section.

## 2. Problem Statement

The higher-order system of a linear transformer can be generally represented as

$$G(\mathrm{s}) = \frac{N^a(\mathrm{s})}{D^b(\mathrm{s})} = \frac{\sum_{i=0}^{n-1} E_i s^i}{\sum_{i=0}^{n} F_i s^i} \tag{1}$$

The $N^n(\mathrm{s})$ and $D^n(\mathrm{s})$ are numerator and denominator polynomial of a higher order. The problem in lower order form represented as follows

$$R_r(\mathrm{s}) = \frac{N^u(\mathrm{s})}{D^u(\mathrm{s})} = \frac{\sum_{i=0}^{u-1} G_i s^i}{\sum_{i=0}^{u} V_i s^i} \tag{2}$$

In the above Eq. (2) $N^u(\mathrm{s})$ and $D^u(\mathrm{s})$ are reduced order numerator and denominator polynomial. The obtained is reduced model inheriting the same property of the original model [1].

## 3. Cauer 3rd Form

The Cauer 3rd form is a mixed form of Cauer 1st and Cauer 2nd form of a continued fraction. This form offers a modest technique and adds a satisfactory approximation for both the transient and steady-state response [22].

The general transfer function of the large linear system is considered as follows.

$$\frac{N(s)}{D(s)} = \frac{B_{21} + B_{22}s + B_{23}s^2 + \ldots + B_{2,m-1}s^{m-2} + B_{2,m}s^{m-1}}{B_{11} + B_{12}s + B_{13}s^2 + \ldots + B_{1,m}s^{m-1} + B_{1,m+1}s^m} \tag{3}$$

Whereas, in Eq. (3) $B_{ij}$ refers to a constant. Executing the long division method in the Eq. (3) the steps designated as follows:

$$\frac{N(s)}{D(s)} = \frac{1}{\frac{B_{11}}{B_{21}} + \frac{B_{1,m+1}s}{B_{2m}} + \frac{B_{31}s + B_{32}s^2 + \ldots + B_{3,m-1}s^{m-1}}{B_{21} + B_{22}s + \ldots + B_{2m}s^{m-1}}} \tag{4}$$

$$B_{31} = B_{12} - \frac{B_{11}B_{22}}{B_{21}} - \frac{B_{1,m+1}B_{21}}{B_{2m}} \tag{5}$$

$$B_{32} = B_{13} - \frac{B_{11}B_{23}}{B_{21}} - \frac{B_{1,m+1}B_{22}}{B_{2m}} \tag{6}$$

Forming the equation from Eqs. (5) and (6) represented in Eq. (7).

$$\frac{N(s)}{D(s)} = \cfrac{1}{\cfrac{B_{11}}{B_{21}} + \cfrac{B_{1,m+1}s}{B_{2n}} + \cfrac{1}{\cfrac{B_{21}}{B_{31}s} + \cfrac{B_{2m}}{B_{3,m-1}} + \cfrac{1}{\cfrac{B_{31}}{B_{41}} + \cfrac{B_{3,m-1}s}{B_{4,m-2}} + \cfrac{1}{\cfrac{B_{41}}{B_{51}s} + \cfrac{B_{4,m-2}}{B_{5,m-3}} + \cfrac{1}{\ddots}}}}} \tag{7}$$

$$= \cfrac{1}{j_1 + j_1^{'}s + \cfrac{1}{\cfrac{j_2}{s} + j_2^{'} + \cfrac{1}{j_3 + j_3^{'}s + \cfrac{1}{\cfrac{j_4}{s} + j_4^{'} + \cfrac{1}{\ddots}}}}} \tag{8}$$

where

$$B_{h,k} = B_{h-2,k+1} - j_{h-2}B_{h-1,k+1} - j_{h-2}^{'}B_{h-1,k}$$
$$h = 3, 4, \cdots, m+1, k = 1, 2, \cdots$$

and $j_q = \dfrac{B_{q,1}}{B_{q+1,1}}$, $j_q^{'} = \dfrac{B_{q,m+2-q}}{B_{q+1,m+1-q}}$ $q = 1, 2, 3, \ldots, B_{q+1,1} \neq 0$ *and* $B_{q+1,m+1-q} \neq 0$

In time domain, Eq. (8) can be signified by state Eq. (9) as follows:

$$\begin{aligned} &B_1\ddot{x} + B_2\dot{x} + B_3x = Cr \\ &w = D_1^T x + D_2^T \dot{x} \\ &x(0) = [0] \text{ and } \dot{x}(0) = [0] \end{aligned} \tag{9}$$

The 2nd order reduced form of Cauer 3rd form is given by

$$G_{lo}(s) = \frac{j_2^{'}s + j_2}{j_1^{'}j_2^{'}s^2 + (j_1j_2^{'} + j_2j_1^{'})s + j_1j_2} \tag{10}$$

## 4. Problem Formulation of Liner Transformer

The transformer is a highly efficient electrical device. The linear transformer has resistance $R_s$ in shunt, $\tau_s$ resistance in series and $R_g$ is resistance with respect to ground and $C_g$ is series and ground capacitance, $L_{11}$ is self-inductance. As the current $I$ passes through the coil mutual inductance developed between the transformer coils. A total current $I$ passing through the coil is given in Eq. (11)

$$I = I_l + I_r + I_c \tag{11}$$

where, $I_l$ Inductance current, $I_r$ resistance current and $I_C$ is capacitance current and from Eq. (11)

$$I = \frac{1}{L}\int edt + Ge + C\frac{de}{dt} \tag{12}$$

Linear section of an air core transformer model with ten coils is represented in Fig. 1.

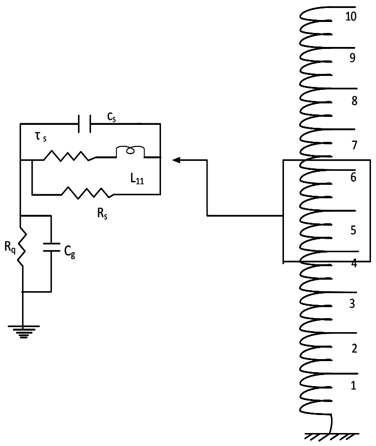


**Fig. 1. Air core transformer.**

Nodal voltage in the linear transformer is *e*, *C*, *G* and 1/*L* capacitance, conductance and nodal inductance inverse matrices. Differentiating Eq. (12) with respect to '*t*'.

$$\frac{dI}{dt} = \frac{1}{L}e + G\frac{de}{dt} + C\frac{d}{dt}\left(\frac{de}{dt}\right) \tag{13}$$

$$w = \frac{de}{dt}, u = \frac{dI}{dt} \tag{14}$$

$$u = \frac{1}{L}e + Gw + C\frac{dw}{dt} \tag{15}$$

By product Eq. (15) and making solution in form state equation

$$C^{-1}u = C^{-1}L^{-1}e + C^{-1}Gw + C^{-1}C\frac{dw}{dt} \tag{16}$$

$$\frac{dw}{dt} = C^{-1}u - C^{-1}L^{-1}e - C^{-1}Gw \tag{17}$$

State variable from of linear section transformer is given in Eq. (18).

$$\dot{x} = Ax + Bu \tag{18}$$

where, $x$ is state vector, $A$ is state matrix and $B$ is input matrix determine using Eqs. (19) - (21).

$$x = \begin{bmatrix} e \\ w \end{bmatrix} \tag{19}$$

$$A = \begin{bmatrix} 0 & 1 \\ -C^{-1}L^{-1} & -C^{-1}G \end{bmatrix} \tag{20}$$

$$B = \begin{bmatrix} 0 \\ C^{-1} \end{bmatrix} \tag{21}$$

According to Khargonekar et al. [23], the transformer parameters for 10 section model are $C_g(F) = 8.5*10^{-10}$, $C_s(F) = 3.4*10^{-12}$, $R_g(\Omega) = 2.1*10^{11}$, $R_s(\Omega) = 1.65*10^5$, $r_s(\Omega) = 22.6$, $L_{1-1}(\text{mH}) = 28.998$, $M_{1-2}(\text{mH}) = 13.537$, $M_{1-3}(\text{mH}) = 6.231$, $M_{1-4}(\text{mH}) = 3.379$, $M_{1-5}(\text{mH}) = 1.987$, $M_{1-6}(\text{mH}) = 1.242$, $M_{1-7}(\text{mH}) = 0.817$, $M_{1-8}(\text{mH}) = 0.560$, $M_{1-9}(\text{mH}) = 0.398$, $M_{1-10}(\text{mH}) = 0.292$. Toivonen and Sagfors [24] explained that the transformer parameter identification is also available.

The state space variable used in the process the poles and zeros are formed from the above values is given as in Table 1.

**Table 1. Zeros and poles of linear transformer.**

| Section | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Zeros | -7.39 | 16.8 | -28.45 | -41.92 | -56.54 | -71.44 | -85.45 | -97.14 | -104.97 | - |
| Poles | -3.06 | -10.37 | -19.84 | -31.33 | 44.51 | -58.69 | -72.94 | -86.39 | -97.59 | -105.09 |

## Linear section of transformer

The transfer function of the linear section of transformer comes out of the 10th order is following in Eq. (22) [23].

$$G(\mathrm{s}) = \frac{\begin{array}{c} s^9 + 510.1s^8 + 1.106e5s^7 + 1.33e7s^6 + 9.690e8s^5 + \\ 4.393e10s^4 + 1.223e12s^3 + 1.980e13s^2 + 1.652e14s + 5.211e14 \end{array}}{\begin{array}{c} s^{10} + 529.81s^9 + 1.202e5s^8 + 1.527e7s^7 + 1.191e9s^6 + 5.892e10s^5 \\ + 1.842e12s^4 + 2.513e13s^3 + 3.784e14s^2 + 1.965e15s + 3.330e15 \end{array}} \tag{22}$$

Reduced form by continued Cauer 3rd [25] form is as following Eq. (23)

$$G_{R4}(\mathrm{s}) = \frac{0.07508s + 1.342}{0.07508s^2 + 1.822s + 8.578} \tag{23}$$

The 2nd order from using Moment matching [1] is given in Eq. (24)

$$G_{R1}(\mathrm{s}) = \frac{0.01914s + 0.1579}{0.0221s^2 + 0.3994s + 1} \tag{24}$$

The 2nd order reduced form of Stability Equation is given in Eq. (25)

$$G_{R2}(\mathrm{s}) = \frac{1.652e14s + 5.211e14}{3.784e14s^2 + 1.965e15s + 3.33e15} \tag{25}$$

The 2nd order by using Cauer 2nd continued fractional method is given by Eq. (26)

$$G_{R3}(\mathrm{s}) = \frac{0.8664s + 7.328}{s^2 + 18.32s + 46.83} \tag{26}$$

Based on studies by Saraswat and Parmar [26], the 2nd order is in the literature and as presented in Eq. (27).

$$G_{R5} = \frac{0.7657s + 4.9786}{s^2 + 13.43s + 31.7322} \tag{27}$$

The response indices Integral Square Error (ISE), Integral Absolute Error (IAE) and Integral Time Absolute Error (ITAE) are given as an Integral Square Error (ISE) is given in Eq. (28).

$$ISE = \int_0^\infty \left[G_c(t) - G_{cr}(t)\right]^2 dt \tag{28}$$

Integral Absolute Error (IAE) is given in Eq. (29)

$$IAE = \int_0^\infty \left|G_c(t) - G_{cr}(t)\right| dt \tag{29}$$

Integral Time Absolute Error (ITAE) is given in Eq. (30).

$$ITAE = \int_0^\infty t.\left|G_c(t) - G_{cr}(t)\right| dt \tag{30}$$

In response indices Eqs. (28), (29) and (30), $G_c(t)$ is the step response of the higher order and $G_a(t)$ is the response of the lower order.

## 5. Result Analysis

The air core transformer has a higher-order transfer function, which is reduced by using the proposed continued fraction Cauer 3rd form method in 2nd order. However, other methods such as MM [1], SE [27], Cauer 2nd form of continued fraction method and 2nd order reduced form from the literature are selected for the comparative study. The step response graph of the original system with 2nd order by MM, SE and by the proposed method is shown in Fig. 2. The Bode plot for the mentioned method is clearly available in Fig. 3. The proposed frequency (rad/s) is 0.103 and magnitude is -16.1(dB). In phase part, the frequency (rad/s) is 0.102 and phase (deg.) is -1.05.

The response of the proposed system as rising time is 0.3437; the settling time is 0.6121, settling minimum is 0.1408, settling max is 0.1564; the peak in the stepresponse is absolute value of the system with time, and this value is 0.1564 and peak time is the time at which the peak value of the system occurs and value of proposed 2nd order results as 1.6500, which is quite good. The frequency response of the original higher-order system and reduced 2nd order system is shown in Fig. 3. Important step response characteristics are clearly indicated in Fig. 2. Taking from Left-hand side the Rise time (seconds) is 0.344, followed by the settling time (second) is 0.612 and the final value is 0.156. Indicated at the end of the characteristic response.

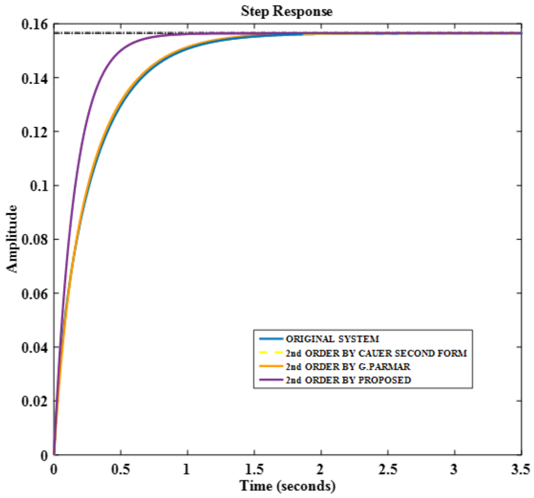


**Fig. 2. Step response of original system with proposed 2nd order, MM and SE.**

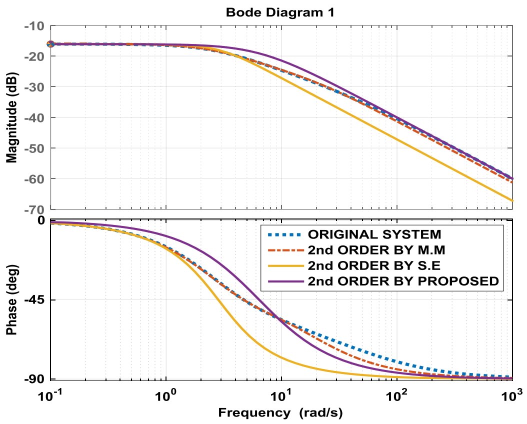


**Fig. 3. Frequency response of original and reduced 2nd order systems.**

According to Saraswat and Parmar [26], in Fig. 4, the original system is compared with the proposed 2nd order reduced and continued fraction Cauer 2nd form, 2nd order and frequency response of the same is represented in Fig. 5. Table 2 gives the comparative step response of original and reduced 2nd order in which rise time of the proposed system is 0.3437, which are better and settling time is 0.6121. However, in Table 3 shows the comparative study of response indices of the proposed system IAE is 0.01877, ITAE 0.03515 and ISE 0.0003323 of the system in which ITAE of the proposed system is superlative among the compared 2nd order reduced system excluding SE.

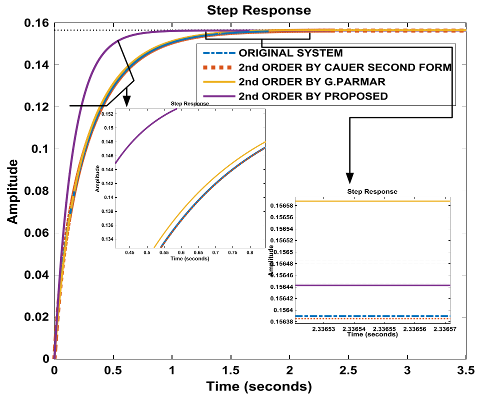


**Fig. 4. Step response of original system with proposed $2^{nd}$ order and with Cauer $2^{nd}$ form Saraswat and Parmar [26].**

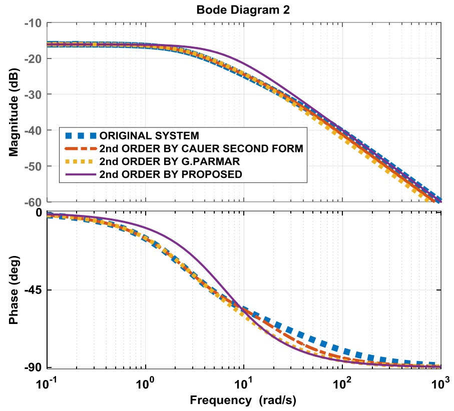


**Fig. 5. Frequency response of original with $2^{nd}$ order reduced systems.**

**Table 2. Comparative step response of $2^{nd}$order with original.**

| Sr. no. | Methods | Rise time | Settling time | Settling minimum | Settling maximum | Peak | Peak time |
|---|---|---|---|---|---|---|---|
| 1 | Original system | 0.6569 | 1.2006 | 0.1410 | 0.1565 | 0.1565 | 3.5598 |
| 2 | $2^{nd}$ Order (proposed) | 0.3437 | 0.6121 | 0.1408 | 0.1564 | 0.1564 | 1.6500 |
| 3 | $2^{nd}$ Order(MM) | 0.6701 | 1.2262 | 0.1421 | 0.1578 | 0.1578 | 2.3775 |
| 4 | $2^{nd}$ Order (SE) | 0.5926 | 0.8688 | 0.1415 | 0.1588 | 0.1588 | 1.3480 |
| 5 | $2^{nd}$ Order (Cauer $2^{nd}$ form) | 0.6565 | 1.2006 | 0.1411 | 0.1564 | 0.1564 | 2.3487 |
| 6 | $2^{nd}$ Order [26] | 0.6376 | 1.1849 | 0.1415 | 0.1566 | 0.1566 | 1.9451 |

**Table 3. Step response indices of original with proposed $2^{nd}$ order reduced system and comparative $2^{nd}$ order.**

| Sr. no. | Methods | ITAE | ISE | IAE |
|---|---|---|---|---|
| 1 | Cauer $3^{rd}$ form | 0.03515 | 0.000332 | 0.01877 |
| 2 | Moment matching | 0.2802 | 3.582e-05 | 0.02578 |
| 3 | Stability equation [3] | 0.01965 | 0.0001019 | 0.01137 |
| 4 | Saraswat and Parmar [26] | 0.08744 | 5.431e-06 | 0.009144 |

## 6. Conclusion

In this manuscript, the higher-order transfer function of a linear transformer is reduced using the Cauer 3$^{rd}$ form of Continued Fractions method. The step response information of the original system, 2$^{nd}$ order reduced system using Cauer 3$^{rd}$ form and the methods available in the literature are compared and enlisted in Table 2. The step responses are considered in terms of rising time and settling time for comparison, and the proposed technique appears to be better as compared to methods in the literature. The comparative analysis of response is also presented in terms of performance indices as ISE, IAE and ITAE. The proposed method appears to better in terms of ITAE as compared to the methods in literature as in Table 3. The proposed reduced order is stable and takes minimum time to settle and have all the important characteristics of the original system as compared to other methods from the literature and clearly mentioned in Tables 2 and 3.

**Nomenclatures**

| | |
|---|---|
| $A$, $B$ | Constant matrices |
| $B_{ij}$ | Coefficients of $N(s)$ and $D(s)$ |
| $C$, $G$ | capacitance and conductance of transformer |
| $C_g$, $C_s$ | Shunt and grounding capacitance, F |
| $D^b(s)$, $N^a(s)$ | Denominator and numerator of $G(s)$ |
| $D(s)$, $N(s)$ | Denominator and numerator of transfer function using Cauer $3^{rd}$ form |
| $D^u(s)$, $N^u(s)$ | Denominator and numerator of $R_r(s)$ |
| $E_i$, $F_i$ | Numerator and denominator coefficients of $G(s)$ |
| $G(s)$ | Transfer function |
| $G_{io}(s)$ | Reduced transfer function using Cauer $3^{rd}$ form |
| $G_i$, $V_i$ | Numerator and denominator coefficients of $R_r(s)$ |
| $I$ | Total current in transformer coil, A |
| $I_c$, $I_l$, $I_r$ | Capacitance, inductance and resistance current, A |
| $j_q$ | Quotients evaluated using Cauer $3^{rd}$ form |
| $L$, $M$ | Self and mutual inductances, H |
| $m$ | Order of transfer function |
| $R_r(s)$ | Reduced transfer function |
| $R_g$, $R_s$ | Shunt and grounding resistance, Ohm |
| $u$, $w$ | Change in voltage and change in current with respect to time |
| $x$ | State vector |

***Greek Symbols***

| | |
|---|---|
| $\ell$ | Nodal voltage in linear transformer, V |
| $\tau_s$ | Series resistance, Ohm |

**Abbreviations**

| | |
|---|---|
| CF | Continued Fraction |
| IAE | Integral Absolute Error |
| ISE | Integral Square Error |

| | |
|---|---|
| ITAE | Integral Time Absolute Error |
| MM | Moment Matching |
| MOR | Model Order Reduction |
| OHO | Original High Order |
| ROM | Reduced Order Model |
| SE | Stability Equation |

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