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磁饱和网络变压器非线性模型建立

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摘要:为了研究外界信号经过变压器后的输入输出特性,基于变压器的高频特性和磁饱和特性,提出了一种变压器的非线性电路模型建立方法,并进行了验证。变压器的高频特性表现为电路模型的寄生参数,构成变压器模型的线性部分。磁饱和特性表现为电路模型的可饱和磁芯参数,构成变压器模型的非线性部分。变压器模型的线性参数和非线性参数可通过实验测量的方法获取。该模型能够预判网络变压器在电缆放电等非正常大信号注入时的输入输出特性。

关键词:网络变压器;高频等效模型;磁饱和;B-H曲线
中图分类号:TM42 **文献标志码**:A

0 引言

网络变压器作为网络接口的重要部件,其作用是将物理层传递的信号与网络接口传递的信号进行电隔离,防止内外干扰,提高传输的可靠性,并且可以滤除噪声,抑制共模干扰。在变压器的选取上,不仅要保证信号传输的完整性,还要考虑在受到外界干扰(例如静电放电)时,其输入输出特性对设备造成的影响。文献[1]发现网络接口终端物理层集成电路(integrated circuit,IC)的失效等级与磁组件的结构有密切关系。文献[2]发现变压器的饱和能够抑制传递到物理层IC端的总能量。文献[3]在研究变压器饱和对交直流电网直流电流分布的影响时,发现变压器的饱和特性对变压器中性点直流电流有助增作用。

目前,部分文献已经对变压器高频等效模型的建立进行了研究,用于分析变压器的趋肤效应、杂散电容等因素对信号传输的影响[4-6]。这些模型虽然考虑了变压器的阻抗特性随传输信号频率的变化,以及绕组漏电感和绕组间电容等因素对传输特性的影响,但是却忽略了变压器磁芯的饱和特性。

文献[7]利用最小二乘法拟合磁化曲线,并通过不同激磁电流下各次谐波的叠加来表征变压器的非线性,但由于谐波在进行叠加时存在一定的误差,因此,该模型并不能准确地反映变压器的饱和特性。文献[8]忽略激磁电阻,通过代表激磁电流的诺顿等效电流源与非线性元件并联,对变压器励磁回路的饱和进行表征,但是其对磁化曲线进行拟合的计算过程十分繁琐,且会出现不收敛的问题。文献[9]采用Jiles-Atherton(J-A)理论模拟磁滞回线,通过确定磁芯材料的相关参数,求解材料磁化密度随外场变化的关系来反映变压器的磁芯饱和。该数学方法非常适合数值计算,广泛应用于电路模拟,但是其计算过程中的参数不易获得。Spice软件的磁芯元件库采用了J-A模型,通过对磁心模型磁化曲线(magnetization curve,B-H曲线)进行修改得到所需B-H曲线,通过参数提取就可以得到J-A模型参数。因此,在Spice软件的Model Editor模块中直接输入测量的B-H曲线数据和其他参数,即可对变压器的磁芯进行定义。

本文建立了一种基于高频特性和磁饱和特性的变压器非线性电路模型。根据变压器的物理特性,通过矢量网络分析仪(vector network analyzer,VNA)、数字电桥等仪器设备,测量变压器的高频特性参数及磁芯的B-H曲线,对变压器可饱和电路模型的建立进行了研究。对比VNA测量和电路模型仿真结

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果,进行了模型的频域验证。使用传输线脉冲(transmission line pulse,TLP)注入的方法,对模型进行了时域验证。

1　变压器高频等效参数提取

结合变压器低频等效模型,并考虑漏电感、磁芯损耗和分布电容等寄生参数的影响,建立了 N∶1 变压器的高频等效电路模型,如图 1 所示。图 1 中:1、3 为输入端;2、4 为输出端;L 为初级绕组电感;C_1 和 C_2 分别为初级绕组电容和次级绕组电容;C 为绕组间电容;R_c 为磁芯损耗电阻;R_1 和 R_2 分别为初级绕组损耗电阻和次级绕组损耗电阻;L_1 和 L_2 分别为初级漏电感和次级漏电感;N∶1 为原线圈和副线圈的匝数比。

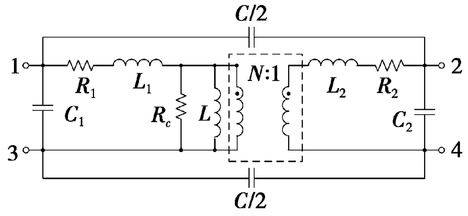
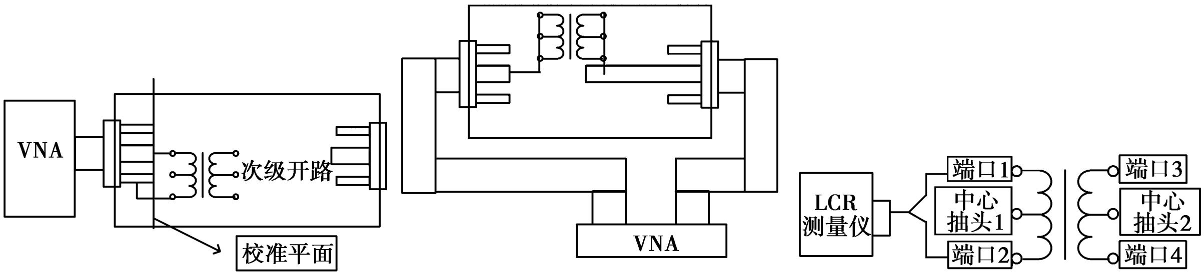


图 1　N∶1 变压器的高频等效电路模型

文献[10-11]对变压器线性模型的建立方法做了说明。本文基于电路中两端口网络理论,通过 VNA 和电感电容电阻(inductance,capacitance,resistance,LCR)数字电桥实验提取高频等效模型中的参数。由于在本文研究的 1∶1 变压器中,导线在磁芯上的绕组方式为在相同的起止位置共同绕组,因此,可认为变压器的初级绕组结构和次级绕组结构具有对称性。变压器高频等效参数的测量集中在初级绕组电感 L、初级绕组电容 C_1、磁芯损耗电阻 R_c、初级漏电感 L_1、绕组间电容 C 和初级绕组损耗电阻 R_1。变压器线性参数测量装置如图 2 所示。装置 a 可以对参数 L、C_1、R_c、L_1 进行测量,见图 2a;装置 b 可以对参数 C 进行测量,见图 2b;装置 c 可以对参数 R_1 进行测量,见图 2c。

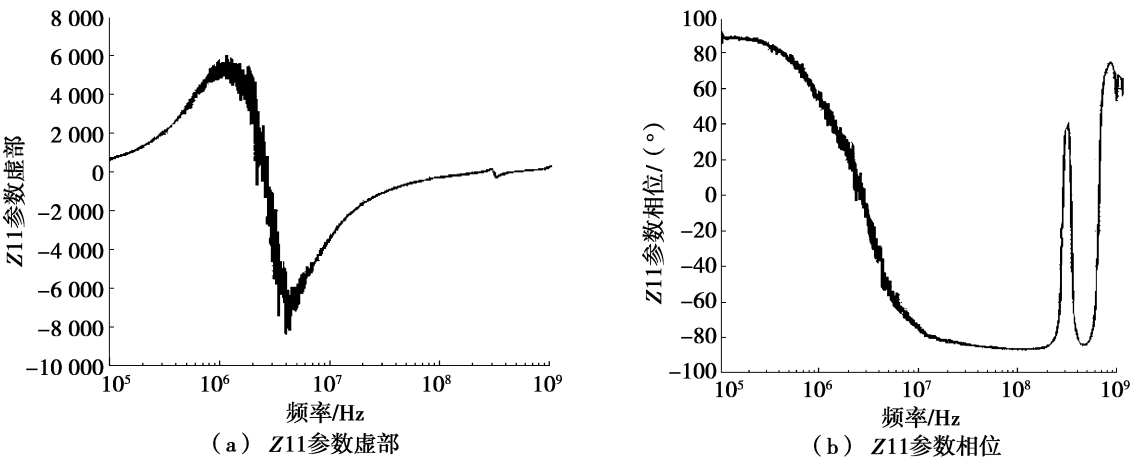


(a)　参数 L、C_1、R_c、L_1 的测量装置 a　　(b)　参数 C 的测量装置 b　　(c)　参数 R_1 的测量装置 c

图 2　变压器线性参数测量装置

1.1　装置 a 中各参数的测量方法

将变压器初级绕组的两个端口分别焊接在微带线端口处和 SMA 接地脚上,保持其他端口和中心抽头处于开路状态,测量变压器端口 1 和端口 3 之间的参数 $S11$,将测量的 $S11$ 参数转换为 $Z11$ 参数,如图 3 所示。图 3a 为 $Z11$ 参数虚部,图 3b 为 $Z11$ 参数相位。



(a)　$Z11$ 参数虚部　　(b)　$Z11$ 参数相位

图 3　使用装置 a 获取的 $Z11$ 参数

使用 $Z11$ 参数计算初级绕组电感 L、初级绕组电容 C_1 和磁芯损耗电阻 R_c,计算公式[2]为:

$$\begin{cases} L = \dfrac{Z11_{\text{imag}}}{2\pi f} \left| Z11_{\text{phase}(f)} \approx 90; \right. \\ C_1 = -\dfrac{1}{2\pi f \cdot Z11_{\text{imag}}} \left| Z11_{\text{phase}(f)} \approx -90; \right. \\ R_c = Z11_{\text{imag}}(f_1) \left| Z11_{\text{phase}(f_1)} = 0。 \right. \end{cases} \tag{1}$$

选择 $Z11$ 的相位为 90°的频段(100 ~ 300 kHz),将计算出的电感取平均值,即为初级绕组电感 L。选择 $Z11$ 的相位为 −90°的频段(10 ~ 100 MHz),将计算出的电容取平均值,即为初级绕组电容 C_1。选择 $Z11$ 的相位为 0°的频率点(2.65 MHz),计算值即为磁芯损耗电阻 R_c。计算结果显示: $L = 0.001$ H,$C_1 = 4.5$ pF,$R_c = 21\ 000\ \Omega$。将变压器的次级绕组短路,重新测量 $S11$ 参数,使用 L 的计算公式,即可得到初级漏电感 $L_1 = 0.04$ mH。

1.2　装置 b 中各参数的测量方法

将变压器的次级绕组端口全部在微带线截断处的一侧短路,次级绕组端口全部在微带线截断处的另一侧短路,测量两端口的 $S21$ 参数。通过 $S21$ 参数计算绕组间电容的公式[2]为:

$$C = \frac{|S21_{\text{mag}}|}{4\pi f \cdot 50}。 \tag{2}$$

选择频段 1 ~ 10 MHz 计算电容,结果显示: 绕组间电容 $C = 17$ pF。

1.3　装置 c 中各参数的测量方法

将 LCR 数字电桥测量参数调为 R,测量夹具的两个夹子分别接变压器初级绕组的两个端口,保持变压器其他端口及中心抽头的开路状态,读取电桥上的测量数据。结果显示: 变压器的初级绕组损耗电阻 $R_1 = 2\ \Omega$。

2　可饱和磁芯的 B-H 曲线获取

磁性材料磁特性的外部表现是材料的磁感应强度 B 和磁场强度 H 的关系。磁感应强度反映了运动电荷被引入磁场中受到磁场力作用的性质。对于在磁场中运动的电荷,根据洛伦兹力计算公式可知磁场对其的作用力。磁场强度沿场中任意闭合路径的线积分只与产生磁场的传导电流有关,与场中介质无关。对于各项同性的磁介质,磁感应强度和磁场强度满足媒介的本构关系,磁导率用来表征磁性材料的导磁能力。对于绕有通电导线的磁芯而言,当通过导线的电流增大时,磁场强度 H 增大,磁感应强度 B 也随之增大,当 B 增大到某一较高数值后,其随 H 增大的幅度很小,即磁芯达到了饱和状态。

变压器的饱和非线性特性可以通过测量磁芯的 B-H 曲线[12]进行表征。磁芯 B-H 曲线的测量装置如图 4 所示。测量方法与图 2a 的方法类似,不同的是,该装置给 VNA 增加了一个外部直流电源。直流电源与 20 Ω 的电阻串联,加载到 VNA 的直流输入端口,并用万用表测量加载到 VNA 的直流电流,这个直流电流经过 VNA 的输出端口,作用到被测量的变压器上。当变压器的初级绕组线圈上有电流流过时,会使原本不显磁的磁芯产生感应磁场。在一定范围内,从 0 V 逐步增大外部直流电源的输出电压,使变压器初级绕组线圈上的通电电流增大,就能够观测到磁饱和现象。

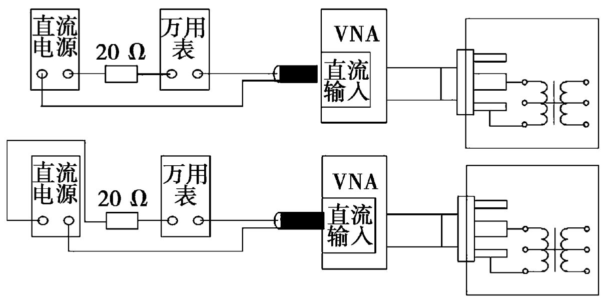


图 4　磁芯 B-H 曲线的测量装置

以 1∶1 变压器为例,改变直流电源的输出大小,使万用表的电流读数从 −496 mA 逐步增大到 496 mA,记录万用表的电流读数和 VNA 对应的 S 参数,计算每一个直流电流读数对应的变压器初级绕组电感 $L(I_{\text{dc}})$。

根据安培定律可知,对于被测的变压器,有:

$$H = \frac{N \cdot I_{dc}}{l_{eff}}, \tag{3}$$

其中: N 为变压器磁环上导线缠绕的匝数; I_{dc} 为加载的直流电流; l_{eff} 为有限环路长度,且满足

$$l_{eff} = \pi\left(\frac{D+d}{2}\right)。 \tag{4}$$

磁感应强度从数值上可以看成是通过与该点磁力线垂直的小面积内单位面积的磁通量。对于均匀磁场,有:

$$B = \frac{\Phi}{A} = \frac{L(I_{dc}) \cdot I_{dc}}{A_{eff} \cdot N}, \tag{5}$$

其中: A_{eff} 为有效磁通面积,满足

$$A_{eff} = \left(\frac{D-d}{2}\right) \cdot h。 \tag{6}$$

对于被测的 1∶1 变压器,代入变压器磁芯尺寸: D 为外直径, d 为内直径, h 为高度, N 为绕组匝数。对于每一个直流电流,有:

$$\begin{gathered} H_i = 3.185 \cdot 1\text{E}3 \cdot I_i; \\ B_i = 2.305 \cdot 1\text{E}3 \cdot \int L(I_{dc})\,\mathrm{d}I_{dc} = 2.305 \cdot 1\text{E}3 \cdot \sum_{n=1}^{n=i} \left(L_n \times (I_n - I_{n-1})\right)。\end{gathered} \tag{7}$$

将初始电感与直流偏置的关系代入式(7),即可获得 B-H 曲线。

再通过式(8)计算变压器磁芯的初始磁导率:

$$\mu_i = \frac{B}{\mu_0 \cdot H} = \frac{L_1 \cdot l_{eff}}{A_{eff} \cdot N^2 \cdot \mu_0}。 \tag{8}$$

将测量的 B-H 曲线数据、有效磁通面积、有效环路面积和初始磁导率输入到 Spice 软件中,对磁芯进行自定义。变压器磁芯 B-H 曲线如图 5 所示。

由于软件中 B-H 曲线的模拟是采用直接输入数据的方式,所以模拟的 B-H 曲线与实测计算出的曲线一致性良好。

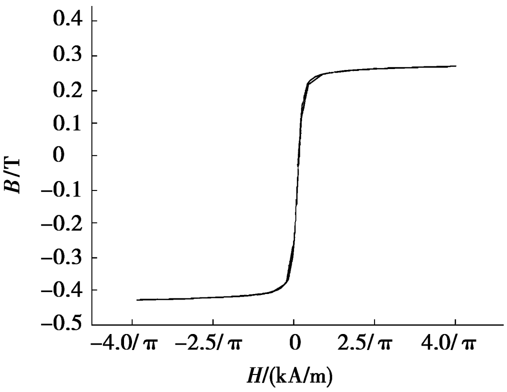


图 5　变压器磁芯 B-H 曲线图

3　变压器非线性模型的建立与验证

最终获得的变压器非线性模型如图 6 所示。图 6 中: K 为非线性磁芯模型; $L_1 \sim L_4$ 为绕组电感 "13"不再是所测量的电感值,而是导线绕组的匝数。

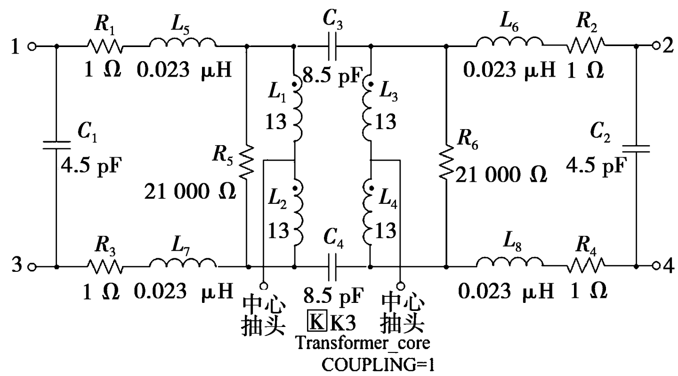


图 6　变压器非线性模型

通过还原测试电路的方式,将变压器的输入阻抗以及传输线脉冲作为干扰源时,对变压器输入输出响应进行对比,对电路模型分别进行了频域验证和时域验证。

3.1　频域验证

对图 6 中变压器的电路模型初级绕组侧的端口 1 和端口 3 之间加载一个交流源 A_{ac},次级绕组和中心抽头与参考信号地之间分别串联 1 TΩ 电阻,相当于开路状态。将仿真模拟和测量计算的 $Z11$ 参数进行对比,如图 7 所示。图 7 的对比结果显示: 100 ~ 300 MHz 时,仿真值和测量值基

本匹配，但是波形在高频范围内有所差异，主要是由于测量计算的线性参数范围都在 300 MHz 以内。

3.2　时域验证

使用传输线脉冲作为信号源，在时域验证变压器非线性电路模型的正确性。图 8 为磁组件的时域测量装置结构图。CT2 电流探头连接示波器测量变压器输入端的电流波形，变压器输出端一个端口连接示波器通道，测量输出端的电压波形。磁组件的时域验证结果波形对比如图 9 所示。

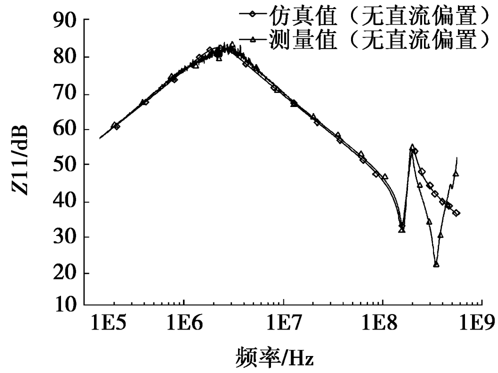


图 7　变压器频域验证结果对比

图 9a 为变压器输出端电压波形，图 9b 为 600 V TLP 信号源输入时的电流波形。当 TLP 信号源的输入端电压较低时，变压器表现为线性，将 TLP 信号源输入变压器的矩形波脉冲传递到变压器的输出端，并且不改变波形的形状。由于测试装置中高倍数衰减器的使用，导致示波器各通道噪声变大，使测量波形中的毛刺较大。随着信号源电压等级的升高，电压和电流波形出现变化，变压器开始出现饱和现象。当变压器出现饱和时，磁组件输入端的电流迅速增大，而输出电压迅速降低。随着信号源电压的增大，电压和电流波形出现突变的时间越来越早，变压器发生饱和的现象越来越明显。

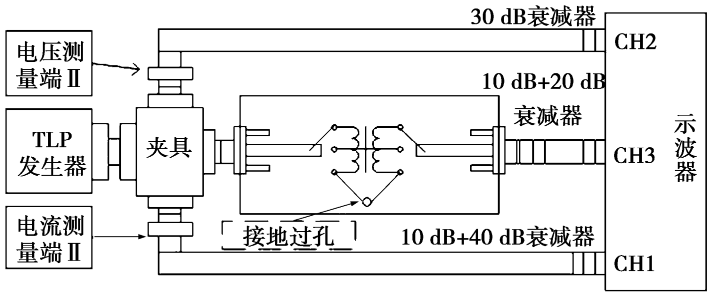
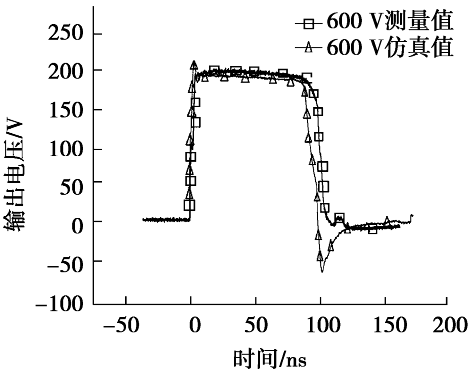
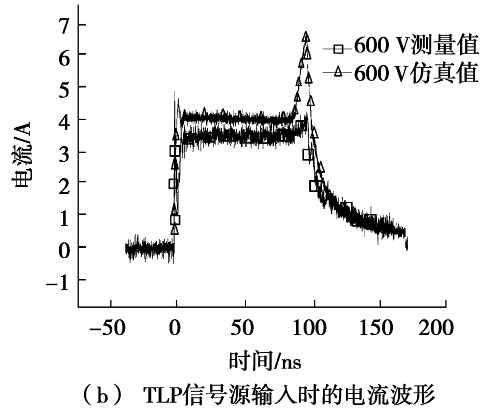


图 8　磁组件的时域测量装置结构图



（a） 变压器输出端电压波形



（b） TLP信号源输入时的电流波形

图 9　磁组件的时域验证结果波形对比

由图 9 可看出: 测量和仿真的电流和电压波形对比结果显示出较好的一致性，特别是在上升沿、电压电流波形峰值和饱和起始时间 3 个参数方面。但在饱和现象发生后，电压波形的下降沿和电流波形的上升沿方面，测量和仿真的结果有所差别，主要是由于变压器的一些高频分量模拟的缺失和 B-H 曲线的测量与模拟的差异性。即使对于同一变压器而言，如果磁芯上导线绕组存在差异，潜在性地破坏了变压器绕组方式的对称性，这也是引起实际测量和高对称性等效电路的模拟结果存在差异的原因。

4 结论

当幅值较大、脉冲时间较长的传输线脉冲放电电流通过变压器的绕线时,由于变压器的磁芯导磁能力有限,磁芯会发生饱和现象,变压器会出现暂态过电压、过电流,引起变压器输入输出两端电压电流剧烈变化。当变压器出现饱和效应时,变压器输入端的电流迅速增大,而输出电压迅速降低。随着信号源电压的增大,饱和出现的时间越来越早。

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· Traffic and Transportation, Energy and Power Engineering ·

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Abstract: Based on the test principle of transient hot-wire method, the air heating process of micro-wire (Φ = 0.06 mm) was measured at horizontal and vertical positions, and the thermal conductivity of air was obtained in different heating powers. The estimation method of air thermal conductivity was adopted considering the influence of natural convection. The calculated value of the thermal conductivity of the estimation method was compared with that of the transient hot wire. The results show that the calculated values of the two methods coincide well when the hot-wire is horizontal placement, but differ greatly from the standard values of the thermal conductivity of air. When the heating power is small, the deviation of the calculated values of the two methods is slightly larger when the micro-wire is vertical placement, and the accuracy of air thermal conductivity calculation based on transient hot-wire method is higher. The deviation of the calculated values of the two methods is small when the heating power is large, and the accuracy of air thermal conductivity calculated by the transient hot-wire method is small. Through theory analysis of natural convection heat transfer intensity on the fine metal wire surface, with the increase of the wire surface temperature, the natural convection heat transfer coefficient of horizontal heating is generally higher than that of vertical heating. The thermal conductivity of transient hot-wire method is affected by the natural convection heat transfer intensity of the heated micro-wire surface.

Key words: thermal engineering; thermal conductivity; transient hot-wire method; natural convection; heating power; micro-wire

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Abstract: In order to solve the contradiction of city bus of steel body with large mass and aluminum body with high cost, the city bus body which middle body was built with aluminum and others with steel was proposed. Five kinds of aluminum alloy sections and connectors were designed to construct the bus body. The initial thickness of sections were identified. The suspension model was built by beam and spring element. The modal characteristics, statics stiffness and strength of steel-aluminum skeleton under the bending-torsional coupling operation condition were analyzed based on optiStructs software. The results indicate that low order intrinsic frequency of steel-aluminum skeleton has little change compared with steel skeleton, but modal shape has a greater difference. When the static strength meets the yield strength of material, the mass is 971.2 kg which is decreased by 146.8 kg compared with steel bus body.

Key words: city bus; steel-aluminum body; finite element method; suspension model; static characteristic

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· Electrical Engineering and Communication, Automation and Computer ·

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Abstract: In order to study input and output characteristics of the network transformer when the external signal was injected, based on the high frequency characteristics and magnetic saturation characteristics of the transformer, a method of establishing the nonlinear circuit model of the transformer was presented and verified. The high frequency characteristic of the transformer was the parasitic parameter of the circuit model, which constituted the linear part of the transformer model. The magnetic saturation characteristic was the saturable core parameter of the circuit model, which constituted the nonlinear part of the transformer model. The linear and non-linear parameters of the transformer model were obtained by experimental measurements. The model can predict the input and output characteristics of the network transformer when the abnormal large-signal such as cable discharge is injected.

Key words: network transformer; high frequency equivalent model; magnetic saturation; B-H curve

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Abstract: To relieve low system throughput and bandwidth utilization rate in additive-increase-multiplicative-decrease algorithm of congestion control, a new reliable congestion window (cwnd) adjustment strategy was proposed. A normal distribution function was built by sampling the round trip delay time, which adapts to the real time network according to updating cwnd dynamically. The reasonability and feasibility of the new strategy and its algorithm was analyzed and proved from the view of mathematics. The results show that compared with original New Reno algorithm and TCP Westwood algorithm, the average value of cwnd of the new algorithm increases by 2.25% and 3.68%, and the packet loss rate decreases by 5.77% and 7.43%, respectively. Meanwhile, the system throughput and the bandwidth utilization rate are promoted. The system throughput increases by 3.09% and 9.25%, and the bandwidth utilization rate increases by 4.46% and 1.37%, respectively. The effect of the new strategy is significant.

Key words: congestion window; strategy; round trip delay time; congestion avoidance; slow start threshold

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• Architecture •

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Abstract: The wind load on the upper and lower surfaces of the roof of the stadium was studied by using the wind tunnel test of rigid model and the simultaneous pressure measurement of the upper and lower surfaces with a half-moon arched long span roof stadium. By arranging the measuring points on the upper and lower surfaces of the roof, the wind pressure coefficients under different wind directions were obtained. The comprehensive wind pressure on the roof surface was analyzed when the upstream building was affected. The influence of the upstream building on the upper and lower surfaces wind pressure of the stadium was also analyzed. The results show that the wind load on the stadium roof is dominated by the upward wind suction. The positive pressure at the roof windward support is larger, and the maximum wind pressure coefficient is 1.4. The negative pressure at the cantilever is larger with a maximum of -2.0. The influence of the upstream building on the roof surface under different wind direction angle is different. The disturbance effect is most obvious under the 60°wind direction angle.

Key words: large span roof; wind tunnel test; wind load; wind pressure coefficient; interference effect

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Abstract: The high loess-filled embankment in Yan'an area was taken as research object. The high pressure consolidation creep tests were carried out under the control of moisture content and compaction degree. The