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考虑系统多运行方式的微电网逆变控制器参数优化方法

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摘要: 微电网中光伏发电出力及负荷波动具有的随机性会造成微电网运行方式的动态变化,为在微电网逆变控制器设计中计及这种动态变化,文中提出了一种基于动态概率特征根分析的微电网逆变控制器参数优化方法。这种方法以特征根的动态概率分布特性为微电网的稳定性评价指标,将微电网中逆变控制器参数的整体优化表示为带不等式约束的非线性优化问题,并利用微分进化算法对该问题进行求解。该方法能够全面准确地计及微电网运行方式多样性对系统稳定性的影响,得到的最优控制参数对系统运行方式的变化具有良好的鲁棒性,仿真结果证明了该方法的有效性。

关键词: 微电网; 小信号稳定; 动态概率特征根; 微分进化算法; 逆变控制器

Optimization Design for Inverter Controllers in Microgrid Considering the System of Multiply Operation Mode

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Abstract: The stochastic of photovoltaic power and demand variation in microgrids can cause dynamic changes of microgrid operation mode. To take this dynamic change into account in the design of inverter controller, a method for inverter controller optimization of parameter based on dynamic probabilistic eigenvalue analysis is proposed. This method uses characteristic root of dynamic probability distribution characteristics as a micro power grid stability evaluation index, taking the micro grid inverter controller parameters in the overall optimization with inequality constraint is represented as the nonlinear optimization problem and uses the evolution algorithm to solve the optimization problem. This method can take account for the influence of the varieties of the real time operation of microgrid on system stability accurately and comprehensively, the optimal control parameters of which has good robustness. Simulation results demonstrate the effectiveness of this method.

Key words: microgrid; small signal stability; dynamic probabilistic eigenvalue; differential evolution algorithm; inverter controller

0 引言

微电网内逆变型微电源(micro source, MS)的控制器设计是当前研究的热点^[1-10]。在孤网运行模式下,微电网内不同特性的MS通常采用不同的控制方式。为保证可再生能源的最大利用率,光伏发电系统等波动较大的MS通常采用最大功率跟踪控制策

略^[1];而像微型燃气轮机、燃料电池及柴油机这样输出稳定的MS,适合根据负荷变化调整出力,维持系统内的功率平衡^[2];储能装置响应迅速,但存储量有限,因此在暂态过程中可利用其抑制频率及电压的大幅波动,在稳态时控制其输出重新归零^[3]。

对于一个包含上述多种类型微电源的微电网,各逆变控制器参数的选择至关重要,然而目前尚没有对所有逆变控制器的参数进行整体优化的系统性方法。文[4-8]中研究了微电网系统的特征值随单个

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控制器参数的变化规律,指出不合理的控制参数将导致系统不稳定,但这只是简单的试错法,耗时且不能保证参数的整体最优性;文[9-10]中利用粒子群算法对微电网内所有控制器的参数进行了整体优化,但没有考虑系统的多运行方式。由于负荷及风力、光伏发电等微电源的输出具有随机性,微电网的运行方式也具有一定的随机波动性,基于一种运行方式所设计的控制器可能在其他运行方式下失效甚至恶化系统的稳定性。因此一种可行的思路是:利用随机量的动态概率模型^[11]来描述光伏发电系统出力与负荷这类即有规律可循又带有随机性的物理现象,并进而研究多运行方式下微电网逆变器的整体参数优化方法。

概率特征根适合描述多运行状态下电力系统的稳定性,但其是静态地采用同一种概率分布特性来描述特征根的随机变化^[12-13],不同时刻特征根的概率特性可能不同。因此,为准确计入微电网运行方式的多样性对特征根分布的影响,文中提出了动态概率特征根分析的概念。与传统概率特征根分析相比,该方法动态考虑不同时刻点特征根的概率特性,能够更加准确地描述特征根的分布规律随时间的变化情况;同时考虑到特征根与运行方式之间确切的解析关系获取困难,采用基于拉丁超立方抽样^[14-15]的蒙特卡洛模拟法来求取特定时刻点特征根的统计特征,从而利用较少的采样点来表征微电网运行方式的分布特性,以有效减少优化问题的计算量,提高求解速度。

综上所述,文中首先建立了包括小型柴油机、储能装置、光伏电池、负荷在内的微电网小信号模型,而后考虑到光伏发电系统出力和负荷具有的随机性,基于拉丁超立方抽样—蒙特卡洛模拟方法,提出了动态概率特征根分析方法,以此为基础构建微电网逆变控制器参数整体优化模型,并利用微分进化算法^[16-18]进行求解,从而获得最优的微电网控制器参数。与传统微电网控制器参数优化方法相比,文中提出的方法考虑了微电网的运行随机性和运行方式多样性,从整体角度出发对微电网控制器参数进行优化,能够有效提高控制器参数的设计准确性,改善多运行方式下微电网的稳定性,优化结果对运行方式的变化具有良好的鲁棒性,特征根分析和时域仿真结果验证了所提方法的正确性和有效性。

1 微电网结构

文中建立的微电网结构与等效电路见图1,孤网运行时系统采用主从控制模式。图1中:柴油机系

统(diesel generator system, DGS)为主控单元,其调速与励磁系统能够维持转子转速与端电压在额定值;储能装置的接口逆变器采用 U/f 下垂控制策略,通过检测端电压幅值与频率的变化,调整输出功率,在暂态过程中对系统的电压和频率进行支撑;由于柴油机的调速系统含有积分控制,具有无差调频特性^[19],因此储能输出在稳态时将重新归零。光伏发电系统(photovoltaic generation system, PVGS)的接口逆变器采用 PQ 控制策略,使其发出的有功跟踪光伏电池的最大输出功率,并令其无功输出为零。

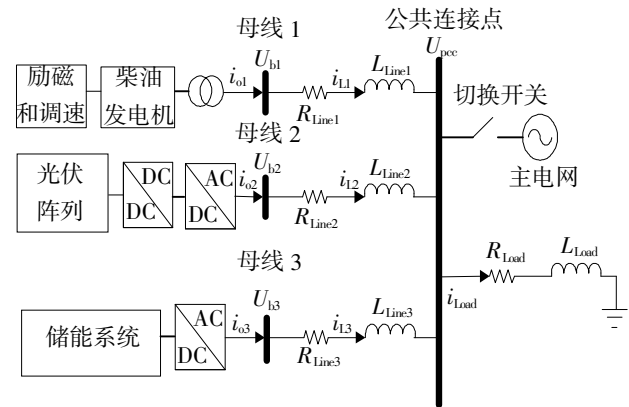


图1 微电网结构与等效电路

Fig. 1 Structure and equivalent circuit of microgrid

2 微电网小信号模型

2.1 柴油发电机系统小信号模型

DGS 中,发电机采用 6 阶模型、励磁系统采用 IEEE DC₁ 模型、柴油机调速器模型见文[20]。根据文[21],将 DGS 的模型在平衡点线性化,可得其状态与输出方程为

$$\dot{\Delta \mathbf{x}}_{\text{DGS}} = \mathbf{A}_{\text{DGS}} \Delta \mathbf{x}_{\text{DGS}} + \mathbf{G}_{\text{DGS}} \Delta \mathbf{U}_{\text{b1qd}}; \quad (1)$$

$$\Delta \mathbf{i}_{\text{o2qd}} = \mathbf{C}_{\text{DGS}} \Delta \mathbf{x}_{\text{DGS}}. \quad (2)$$

式(1)、(2)中: $\Delta \mathbf{x}_{\text{DGS}}$ 为 DGS 的状态变量; $\mathbf{A}_{\text{DGS}}$ 、 $\mathbf{G}_{\text{DGS}}$ 及 $\mathbf{C}_{\text{DGS}}$ 为 DGS 的状态矩阵、电压系数矩阵及输出矩阵^[21]。

2.2 光伏发电系统小信号模型

PVGS 并网逆变器控制原理见图2。图2中: R_{cl} 、 L_{cl} 为等效连接电阻和电感; $U_{\text{dc1}}^{\text{ref}}$ 、 Q_1^{ref} 直流侧电容电压和 PVGS 输出无功功率给定值;锁相环用以提供 abc 到 qd 坐标系变换所需的相位角 θ_1 及 qd 坐标系的旋转频率 ω_1 ^[12]。由图2可见,WT 电网侧变流器采用直流电压外环、电流内环的双环控制方式;其中外环直流电压控制器用于保证直流侧电容电压恒定^[18],使逆变器稳定输出太阳能电池捕获的功率,同时控制流向微电网的无功功率(通常设定为零);内环电流控制器用于实现有功无功的解耦控制,以产生 PVGS 逆变器的参考电压 $U_{\text{ob1qd}}^{\text{ref}}$ 。

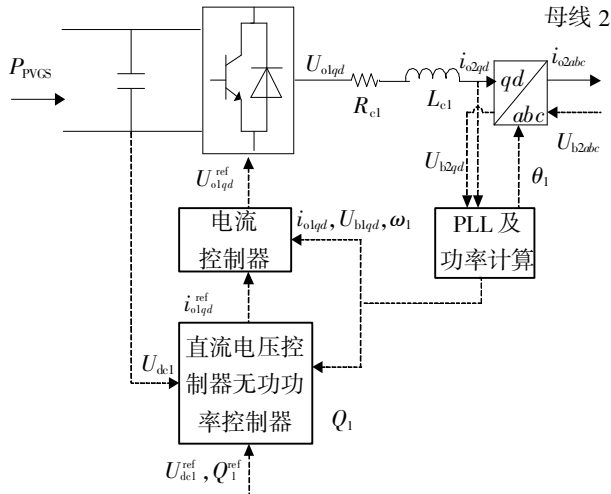


图2 光伏发电系统逆变器控制与接口电路

Fig. 2 Inverter control and interface power circuit of PVS

根据文[8-10]将 PVGS 的模型在平衡点线性化, 可 PVGS 的状态及输出方程见式(3)、(4)。

$$\dot{\Delta \mathbf{x}}_{\text{PVGS}} = \mathbf{A}_{\text{PVGS}} \Delta \mathbf{x}_{\text{PVGS}} + \mathbf{G}_{\text{PVGS}} \Delta \mathbf{U}_{\text{b}2qd}; \quad (3)$$

$$\Delta \mathbf{i}_{\text{o}1qd} = \mathbf{C}_{\text{PVGS}} \Delta \mathbf{x}_{\text{PVGS}}. \quad (4)$$

式(3)、(4)中: 状态变量 $\Delta \mathbf{x}_{\text{PVGS}} = [\Delta \Phi_{\text{pll}} \Delta \theta_1 \Delta \Phi_{d1} \Delta \Phi_{q1} \Delta \Phi_{d1}' \Delta \Phi_{q1}' \Delta i_{\text{o}2d} \Delta i_{\text{o}2q}]^T$, 其中 $\Delta \Phi_{\text{pll}}$ 、 $\Delta \theta_1$ 为 PLL 环节的状态变量; $\Delta \Phi_{d1}$ 、 $\Delta \Phi_{q1}$ 为有功、无功控制环节的状态变量; $\Delta \Phi_{d1}'$ 、 $\Delta \Phi_{q1}'$ 为 d 、 q 轴电流控制环节的状态变量; $\Delta i_{\text{o}2d}$ 、 $\Delta i_{\text{o}2q}$ 为 PVGS 向微电网中注入电流的 d 、 q 分量。

2.3 储能系统小信号模型

储能系统逆变器控制及接口电路模型见图 3。其中电流控制器实现逆变器交流侧电压的直接控制, 用于快速跟踪参考电流; 功率控制器根据输出功率的变化提供电流参考信号; 下垂控制器通过频率—有功、电压—无功下垂特性产生功率调节量; PLL 用以提供 QD 到 $q2d2$ 坐标变换所需的相位角 θ_2 及 $q2d2$ 坐标系的旋转频率 ω_2 。

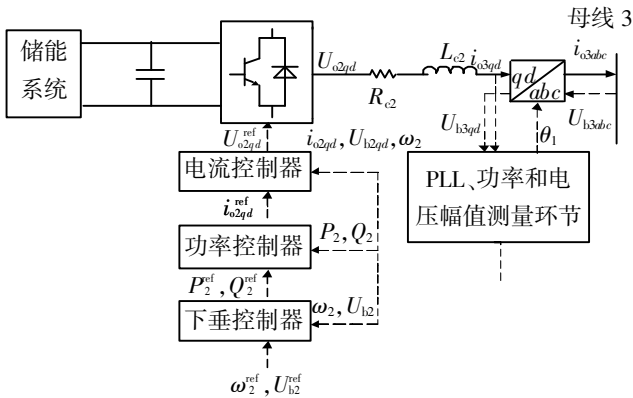


图3 储能系统逆变器控制与接口电路

Fig. 3 Inverter control and interface power circuit of ESS

根据文[8-10]对 ESS 的模型在平衡点线性化, 可得 ESS 的状态与输出方程

$$\dot{\Delta \mathbf{x}}_{\text{ESS}} = \mathbf{A}_{\text{ESS}} \Delta \mathbf{x}_{\text{ESS}} + \mathbf{G}_{\text{ESS}} \Delta \mathbf{U}_{\text{b}3qd}; \quad (5)$$

$$\Delta \mathbf{i}_{\text{o}1qd} = \mathbf{C}_{\text{ESS}} \Delta \mathbf{x}_{\text{ESS}}. \quad (6)$$

式(5)、(6)中: 状态变量 $\Delta \mathbf{x}_{\text{ESS}} = [\Delta \Phi_{\text{pll}2} \Delta \theta_2 \Delta \Phi_{\text{o}2} \Delta \Phi_{d2} \Delta \Phi_{q2} \Delta \Phi_{d2}' \Delta \Phi_{q2}' \Delta i_{\text{o}3d} \Delta i_{\text{o}3q}]^T$, $\mathbf{A}_{\text{ESS}}$ 、 $\mathbf{G}_{\text{ESS}}$ 和 $\mathbf{C}_{\text{ESS}}$ 为 ESS 的状态矩阵、电压系数矩阵及输出矩阵。

2.4 线路及负荷小信号模型

图 2 中线路的线性化模型见式(7)。

$$\dot{\Delta \mathbf{i}}_{\text{LQD}} = \mathbf{A}_{\text{NET}} \Delta \mathbf{i}_{\text{LQD}} + \mathbf{G}_{\text{NET}} \Delta \mathbf{U}_{\text{bQD}}. \quad (7)$$

式(7)中: $\Delta \mathbf{i}_{\text{LQD}} = [\Delta i_{\text{LQD}1} \Delta i_{\text{LQD}2} \Delta i_{\text{LQD}3}]^T$; $\Delta \mathbf{U}_{\text{bQD}} = [\Delta U_{\text{bQD}1} \Delta U_{\text{bQD}2} \Delta U_{\text{bQD}3}]^T$ 。

2.5 微电网完整小信号模型

利用节点 1-3 的网络关系, 根据式(1)、(3)、(5)、(7)可得微电网的状态方程

$$\dot{\Delta \mathbf{x}} = \mathbf{A} \Delta \mathbf{x}. \quad (8)$$

式(8)中: $\Delta \mathbf{x} = [\Delta \mathbf{x}_{\text{DGS}} \Delta \mathbf{x}_{\text{ESS}} \Delta \mathbf{x}_{\text{PVS}} \Delta \mathbf{i}_{\text{LQD}}]^T$, 需要强调的是: 状态矩阵 $\mathbf{A}$ 中的元素是系统中各逆变控制器参数及状态、代数变量初始值的函数, 因此系统的特征根分布情况取决于光伏发电及储能系统逆变控制器参数的选择及系统运行方式的变化。

3 基于动态概率特征根分析的微电网逆变控制器参数优化

3.1 微电网动态概率特征根分析

为了计及光伏发电及负荷的随机波动性对微电网逆变控制器参数设计的影响, 需要预先获得微电网运行过程中可能出现的各种场景, 即建立 PVGS 输出功率及负荷需求的预测模型, 随机波动量的预测模型可由式(9)来描述:

$$W(t) = P(t) + D(t). \quad (9)$$

式(9)中: $P(t)$ 为基础函数, 用来反映 $W(t)$ 中按规律变化的成分; $D(t)$ 为随机变量, 用来反映 $W(t)$ 中的随机波动成分, 光伏发电系统出力与负荷的动态概率模型见图 4、5。

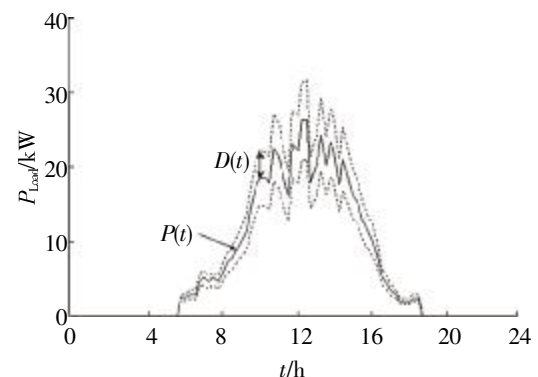


图4 光伏发电系统出力的动态概率模型

Fig. 4 Dynamic probability model for the output of PVS

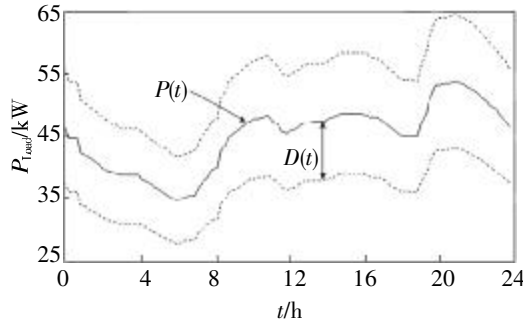


图5 负荷的动态概率模型

Fig. 5 Dynamic probability model for load

图4中将光伏发电系统出力与负荷的预测值作为基础函数 $P(t)$, 并假设 $D(t)$ 满足正态分布, 最大波动幅度为 20%。

光伏发电系统出力与负荷的动态概率模型揭示了微电网的运行方式在时间轴上的概率分布特性; 由于特征根是系统运行方式的函数, 因此在不同的时刻点上, 可基于运行方式的概率模型确定相应特征根的分布特征, 定义这种考虑特征根的分布随着时间发生变化的分析方法为动态概率特征根分析。

3.2 拉丁超立方采样理论

该方法由两步构成:

1) 采样。假设抽样次数为 N , $X_1, X_2, \dots, X_K$ 为待求概率问题的 K 个输入随机变量, $X_k, k \in [1, K]$ 的累积概率分布函数为 $Y_k = F_k(X_k)$, 该分布函数的取值范围 $[0, 1]$ 被等分成 N 个子区间, 选择每个区间的中点作为 Y_k 的采样值, 然后由 CDF 的逆函数 $F_k^{-1}(Y_k)$ 求得 X_k 的采样值, 采样示意图见图 6。 X_k 的第 n 个采样值为: $x_{kn} = F_k^{-1}[(n-0.5)/N]$ 。

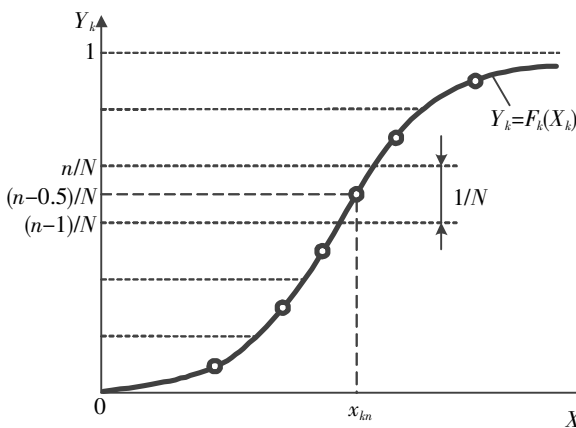


图6 拉丁超立方采样示意图

Fig. 6 Sampling step in Latin hypercube sampling

2) 排列。将每一个随机变量的采样值排成矩阵的一行。当 K 个输入随机变量采样结束, 所有的采样值 x_{kn} 形成一个 $K \times N$ 阶的初始采样矩阵 X 。采用 Gram-Schmidt 序列正交化方法排列各行采样点的顺序, 使不同随机变量采样值的相关性趋于最小。

最终形成的采样矩阵 X 的行为某个随机变量的所有采样值; 列为一次随机模拟中各随机变量的输入值。分别对不同时刻点 X 中的每一列所代表的运行方式进行确定性的小干扰分析, 从结果中即能够统计出当前时刻点特征根的分布情况。

3.3 逆变器参数优化模型

特征根在复平面的位置决定了系统的稳定性和动态性能的优劣。对于 t 时刻系统的第 m 个特征根 $\lambda_{m,t} = \alpha_{m,t} \pm j\beta_{m,t}$, 若其实部 $\alpha_{m,t}$ 具有均值 $\bar{\alpha}_{m,t}$ 和标准差 $\sigma_{m,t}$, 则 $\alpha_{m,t}$ 位于区间 $[-\infty, \bar{\alpha}_{m,t} + 4\sigma_{m,t}]$ 的概率为 0.999 9, 非常接近于 1^[11]; 因此在设计逆变控制器参数时应保证该区间完全位于复平面的左半平面, 即区间上界 $\alpha_{m,t}' = \bar{\alpha}_{m,t} + 4\sigma_{m,t} \leq 0$, 且 $\alpha_{m,t}'$ 距离虚轴的距离应尽可能的远。根据以上分析, 文中采用 $\alpha_{m,t}'$ 来评估 t 时刻微电网在多运行方式下的稳定性。

对于所考虑的整个时间区间, 微电网逆变器参数设计问题可转化为优化问题, 目标函数定义为

$$J = \max\{\alpha_{m,t}', m=1, \dots, M; t=1, \dots, T\}. \quad (10)$$

式(10)中, M, T 分别为系统的特征根数与所考虑的时刻点数。式(10)所示目标函数为在整个时间区间所有特征根实部的最大上界, 优化的目的是使该上界尽可能的向远离虚轴的方向左移, 这样的优化目标保证参数在不同运行方式下整体的最优性, 考虑到各参数的限制, 逆变控制器最优设计为:

$$\begin{cases} \min J \\ \mu \\ \text{s.t. } \mu^{\min} \leq \mu \leq \mu^{\max} \end{cases}. \quad (11)$$

式(11)中: 优化变量 μ 为光伏发电和储能系统逆变控制器的参数 $K_{p1}, K_{i1}, K_{p2}, K_{i2}, K_{p3}, K_{i3}, K_{p4}, K_{i4}, K_{p5}, K_{i5}, K_{p6}, K_{i6}, K_{p7}, K_{i7}, K_{p8}, K_{i8}, K_{p9}, K_{i9}, K_{p10}, K_{i10}, K_{p11}, K_{i11}, K_{p12}, K_{i12}, K_{p13}, K_{i13}, K_{p14}, K_{i14}, K_{p15}, K_{i15}, K_{p16}, K_{i16}, K_{p17}, K_{i17}, K_{p18}, K_{i18}, K_{p19}, K_{i19}, K_{p20}, K_{i20}, K_{p21}, K_{i21}, K_{p22}, K_{i22}, K_{p23}, K_{i23}, K_{p24}, K_{i24}, K_{p25}, K_{i25}, K_{p26}, K_{i26}, K_{p27}, K_{i27}, K_{p28}, K_{i28}, K_{p29}, K_{i29}, K_{p30}, K_{i30}, K_{p31}, K_{i31}, K_{p32}, K_{i32}, K_{p33}, K_{i33}, K_{p34}, K_{i34}, K_{p35}, K_{i35}, K_{p36}, K_{i36}, K_{p37}, K_{i37}, K_{p38}, K_{i38}, K_{p39}, K_{i39}, K_{p40}, K_{i40}, K_{p41}, K_{i41}, K_{p42}, K_{i42}, K_{p43}, K_{i43}, K_{p44}, K_{i44}, K_{p45}, K_{i45}, K_{p46}, K_{i46}, K_{p47}, K_{i47}, K_{p48}, K_{i48}, K_{p49}, K_{i49}, K_{p50}, K_{i50}, K_{p51}, K_{i51}, K_{p52}, K_{i52}, K_{p53}, K_{i53}, K_{p54}, K_{i54}, K_{p55}, K_{i55}, K_{p56}, K_{i56}, K_{p57}, K_{i57}, K_{p58}, K_{i58}, K_{p59}, K_{i59}, K_{p60}, K_{i60}, K_{p61}, K_{i61}, K_{p62}, K_{i62}, K_{p63}, K_{i63}, K_{p64}, K_{i64}, K_{p65}, K_{i65}, K_{p66}, K_{i66}, K_{p67}, K_{i67}, K_{p68}, K_{i68}, K_{p69}, K_{i69}, K_{p70}, K_{i70}, K_{p71}, K_{i71}, K_{p72}, K_{i72}, K_{p73}, K_{i73}, K_{p74}, K_{i74}, K_{p75}, K_{i75}, K_{p76}, K_{i76}, K_{p77}, K_{i77}, K_{p78}, K_{i78}, K_{p79}, K_{i79}, K_{p80}, K_{i80}, K_{p81}, K_{i81}, K_{p82}, K_{i82}, K_{p83}, K_{i83}, K_{p84}, K_{i84}, K_{p85}, K_{i85}, K_{p86}, K_{i86}, K_{p87}, K_{i87}, K_{p88}, K_{i88}, K_{p89}, K_{i89}, K_{p90}, K_{i90}, K_{p91}, K_{i91}, K_{p92}, K_{i92}, K_{p93}, K_{i93}, K_{p94}, K_{i94}, K_{p95}, K_{i95}, K_{p96}, K_{i96}, K_{p97}, K_{i97}, K_{p98}, K_{i98}, K_{p99}, K_{i99}, K_{p100}, K_{i100}, K_{p101}, K_{i101}, K_{p102}, K_{i102}, K_{p103}, K_{i103}, K_{p104}, K_{i104}, K_{p105}, K_{i105}, K_{p106}, K_{i106}, K_{p107}, K_{i107}, K_{p108}, K_{i108}, K_{p109}, K_{i109}, K_{p110}, K_{i110}, K_{p111}, K_{i111}, K_{p112}, K_{i112}, K_{p113}, K_{i113}, K_{p114}, K_{i114}, K_{p115}, K_{i115}, K_{p116}, K_{i116}, K_{p117}, K_{i117}, K_{p118}, K_{i118}, K_{p119}, K_{i119}, K_{p120}, K_{i120}, K_{p121}, K_{i121}, K_{p122}, K_{i122}, K_{p123}, K_{i123}, K_{p124}, K_{i124}, K_{p125}, K_{i125}, K_{p126}, K_{i126}, K_{p127}, K_{i127}, K_{p128}, K_{i128}, K_{p129}, K_{i129}, K_{p130}, K_{i130}, K_{p131}, K_{i131}, K_{p132}, K_{i132}, K_{p133}, K_{i133}, K_{p134}, K_{i134}, K_{p135}, K_{i135}, K_{p136}, K_{i136}, K_{p137}, K_{i137}, K_{p138}, K_{i138}, K_{p139}, K_{i139}, K_{p140}, K_{i140}, K_{p141}, K_{i141}, K_{p142}, K_{i142}, K_{p143}, K_{i143}, K_{p144}, K_{i144}, K_{p145}, K_{i145}, K_{p146}, K_{i146}, K_{p147}, K_{i147}, K_{p148}, K_{i148}, K_{p149}, K_{i149}, K_{p150}, K_{i150}, K_{p151}, K_{i151}, K_{p152}, K_{i152}, K_{p153}, K_{i153}, K_{p154}, K_{i154}, K_{p155}, K_{i155}, K_{p156}, K_{i156}, K_{p157}, K_{i157}, K_{p158}, K_{i158}, K_{p159}, K_{i159}, K_{p160}, K_{i160}, K_{p161}, K_{i161}, K_{p162}, K_{i162}, K_{p163}, K_{i163}, K_{p164}, K_{i164}, K_{p165}, K_{i165}, K_{p166}, K_{i166}, K_{p167}, K_{i167}, K_{p168}, K_{i168}, K_{p169}, K_{i169}, K_{p170}, K_{i170}, K_{p171}, K_{i171}, K_{p172}, K_{i172}, K_{p173}, K_{i173}, K_{p174}, K_{i174}, K_{p175}, K_{i175}, K_{p176}, K_{i176}, K_{p177}, K_{i177}, K_{p178}, K_{i178}, K_{p179}, K_{i179}, K_{p180}, K_{i180}, K_{p181}, K_{i181}, K_{p182}, K_{i182}, K_{p183}, K_{i183}, K_{p184}, K_{i184}, K_{p185}, K_{i185}, K_{p186}, K_{i186}, K_{p187}, K_{i187}, K_{p188}, K_{i188}, K_{p189}, K_{i189}, K_{p190}, K_{i190}, K_{p191}, K_{i191}, K_{p192}, K_{i192}, K_{p193}, K_{i193}, K_{p194}, K_{i194}, K_{p195}, K_{i195}, K_{p196}, K_{i196}, K_{p197}, K_{i197}, K_{p198}, K_{i198}, K_{p199}, K_{i199}, K_{p200}, K_{i200}, K_{p201}, K_{i201}, K_{p202}, K_{i202}, K_{p203}, K_{i203}, K_{p204}, K_{i204}, K_{p205}, K_{i205}, K_{p206}, K_{i206}, K_{p207}, K_{i207}, K_{p208}, K_{i208}, K_{p209}, K_{i209}, K_{p210}, K_{i210}, K_{p211}, K_{i211}, K_{p212}, K_{i212}, K_{p213}, K_{i213}, K_{p214}, K_{i214}, K_{p215}, K_{i215}, K_{p216}, K_{i216}, K_{p217}, K_{i217}, K_{p218}, K_{i218}, K_{p219}, K_{i219}, K_{p220}, K_{i220}, K_{p221}, K_{i221}, K_{p222}, K_{i222}, K_{p223}, K_{i223}, K_{p224}, K_{i224}, K_{p225}, K_{i225}, K_{p226}, K_{i226}, K_{p227}, K_{i227}, K_{p228}, K_{i228}, K_{p229}, K_{i229}, K_{p230}, K_{i230}, K_{p231}, K_{i231}, K_{p232}, K_{i232}, K_{p233}, K_{i233}, K_{p234}, K_{i234}, K_{p235}, K_{i235}, K_{p236}, K_{i236}, K_{p237}, K_{i237}, K_{p238}, K_{i238}, K_{p239}, K_{i239}, K_{p240}, K_{i240}, K_{p241}, K_{i241}, K_{p242}, K_{i242}, K_{p243}, K_{i243}, K_{p244}, K_{i244}, K_{p245}, K_{i245}, K_{p246}, K_{i246}, K_{p247}, K_{i247}, K_{p248}, K_{i248}, K_{p249}, K_{i249}, K_{p250}, K_{i250}, K_{p251}, K_{i251}, K_{p252}, K_{i252}, K_{p253}, K_{i253}, K_{p254}, K_{i254}, K_{p255}, K_{i255}, K_{p256}, K_{i256}, K_{p257}, K_{i257}, K_{p258}, K_{i258}, K_{p259}, K_{i259}, K_{p260}, K_{i260}, K_{p261}, K_{i261}, K_{p262}, K_{i262}, K_{p263}, K_{i263}, K_{p264}, K_{i264}, K_{p265}, K_{i265}, K_{p266}, K_{i266}, K_{p267}, K_{i267}, K_{p268}, K_{i268}, K_{p269}, K_{i269}, K_{p270}, K_{i270}, K_{p271}, K_{i271}, K_{p272}, K_{i272}, K_{p273}, K_{i273}, K_{p274}, K_{i274}, K_{p275}, K_{i275}, K_{p276}, K_{i276}, K_{p277}, K_{i277}, K_{p278}, K_{i278}, K_{p279}, K_{i279}, K_{p280}, K_{i280}, K_{p281}, K_{i281}, K_{p282}, K_{i282}, K_{p283}, K_{i283}, K_{p284}, K_{i284}, K_{p285}, K_{i285}, K_{p286}, K_{i286}, K_{p287}, K_{i287}, K_{p288}, K_{i288}, K_{p289}, K_{i289}, K_{p290}, K_{i290}, K_{p291}, K_{i291}, K_{p292}, K_{i292}, K_{p293}, K_{i293}, K_{p294}, K_{i294}, K_{p295}, K_{i295}, K_{p296}, K_{i296}, K_{p297}, K_{i297}, K_{p298}, K_{i298}, K_{p299}, K_{i299}, K_{p300}, K_{i300}, K_{p301}, K_{i301}, K_{p302}, K_{i302}, K_{p303}, K_{i303}, K_{p304}, K_{i304}, K_{p305}, K_{i305}, K_{p306}, K_{i306}, K_{p307}, K_{i307}, K_{p308}, K_{i308}, K_{p309}, K_{i309}, K_{p310}, K_{i310}, K_{p311}, K_{i311}, K_{p312}, K_{i312}, K_{p313}, K_{i313}, K_{p314}, K_{i314}, K_{p315}, K_{i315}, K_{p316}, K_{i316}, K_{p317}, K_{i317}, K_{p318}, K_{i318}, K_{p319}, K_{i319}, K_{p320}, K_{i320}, K_{p321}, K_{i321}, K_{p322}, K_{i322}, K_{p323}, K_{i323}, K_{p324}, K_{i324}, K_{p325}, K_{i325}, K_{p326}, K_{i326}, K_{p327}, K_{i327}, K_{p328}, K_{i328}, K_{p329}, K_{i329}, K_{p330}, K_{i330}, K_{p331}, K_{i331}, K_{p332}, K_{i332}, K_{p333}, K_{i333}, K_{p334}, K_{i334}, K_{p335}, K_{i335}, K_{p336}, K_{i336}, K_{p337}, K_{i337}, K_{p338}, K_{i338}, K_{p339}, K_{i339}, K_{p340}, K_{i340}, K_{p341}, K_{i341}, K_{p342}, K_{i342}, K_{p343}, K_{i343}, K_{p344}, K_{i344}, K_{p345}, K_{i345}, K_{p346}, K_{i346}, K_{p347}, K_{i347}, K_{p348}, K_{i348}, K_{p349}, K_{i349}, K_{p350}, K_{i350}, K_{p351}, K_{i351}, K_{p352}, K_{i352}, K_{p353}, K_{i353}, K_{p354}, K_{i354}, K_{p355}, K_{i355}, K_{p356}, K_{i356}, K_{p357}, K_{i357}, K_{p358}, K_{i358}, K_{p359}, K_{i359}, K_{p360}, K_{i360}, K_{p361}, K_{i361}, K_{p362}, K_{i362}, K_{p363}, K_{i363}, K_{p364}, K_{i364}, K_{p365}, K_{i365}, K_{p366}, K_{i366}, K_{p367}, K_{i367}, K_{p368}, K_{i368}, K_{p369}, K_{i369}, K_{p370}, K_{i370}, K_{p371}, K_{i371}, K_{p372}, K_{i372}, K_{p373}, K_{i373}, K_{p374}, K_{i374}, K_{p375}, K_{i375}, K_{p376}, K_{i376}, K_{p377}, K_{i377}, K_{p378}, K_{i378}, K_{p379}, K_{i379}, K_{p380}, K_{i380}, K_{p381}, K_{i381}, K_{p382}, K_{i382}, K_{p383}, K_{i383}, K_{p384}, K_{i384}, K_{p385}, K_{i385}, K_{p386}, K_{i386}, K_{p387}, K_{i387}, K_{p388}, K_{i388}, K_{p389}, K_{i389}, K_{p390}, K_{i390}, K_{p391}, K_{i391}, K_{p392}, K_{i392}, K_{p393}, K_{i393}, K_{p394}, K_{i394}, K_{p395}, K_{i395}, K_{p396}, K_{i396}, K_{p397}, K_{i397}, K_{p398}, K_{i398}, K_{p399}, K_{i399}, K_{p400}, K_{i400}, K_{p401}, K_{i401}, K_{p402}, K_{i402}, K_{p403}, K_{i403}, K_{p404}, K_{i404}, K_{p405}, K_{i405}, K_{p406}, K_{i406}, K_{p407}, K_{i407}, K_{p408}, K_{i408}, K_{p409}, K_{i409}, K_{p410}, K_{i410}, K_{p411}, K_{i411}, K_{p412}, K_{i412}, K_{p413}, K_{i413}, K_{p414}, K_{i414}, K_{p415}, K_{i415}, K_{p416}, K_{i416}, K_{p417}, K_{i417}, K_{p418}, K_{i418}, K_{p419}, K_{i419}, K_{p420}, K_{i420}, K_{p421}, K_{i421}, K_{p422}, K_{i422}, K_{p423}, K_{i423}, K_{p424}, K_{i424}, K_{p425}, K_{i425}, K_{p426}, K_{i426}, K_{p427}, K_{i427}, K_{p428}, K_{i428}, K_{p429}, K_{i429}, K_{p430}, K_{i430}, K_{p431}, K_{i431}, K_{p432}, K_{i432}, K_{p433}, K_{i433}, K_{p434}, K_{i434}, K_{p435}, K_{i435}, K_{p436}, K_{i436}, K_{p437}, K_{i437}, K_{p438}, K_{i438}, K_{p439}, K_{i439}, K_{p440}, K_{i440}, K_{p441}, K_{i441}, K_{p442}, K_{i442}, K_{p443}, K_{i443}, K_{p444}, K_{i444}, K_{p445}, K_{i445}, K_{p446}, K_{i446}, K_{p447}, K_{i447}, K_{p448}, K_{i448}, K_{p449}, K_{i449}, K_{p450}, K_{i450}, K_{p451}, K_{i451}, K_{p452}, K_{i452}, K_{p453}, K_{i453}, K_{p454}, K_{i454}, K_{p455}, K_{i455}, K_{p456}, K_{i456}, K_{p457}, K_{i457}, K_{p458}, K_{i458}, K_{p459}, K_{i459}, K_{p460}, K_{i460}, K_{p461}, K_{i461}, K_{p462}, K_{i462}, K_{p463}, K_{i463}, K_{p464}, K_{i464}, K_{p465}, K_{i465}, K_{p466}, K_{i466}, K_{p467}, K_{i467}, K_{p468}, K_{i468}, K_{p469}, K_{i469}, K_{p470}, K_{i470}, K_{p471}, K_{i471}, K_{p472}, K_{i472}, K_{p473}, K_{i473}, K_{p474}, K_{i474}, K_{p475}, K_{i475}, K_{p476}, K_{i476}, K_{p477}, K_{i477}, K_{p478}, K_{i478}, K_{p479}, K_{i479}, K_{p480}, K_{i480}, K_{p481}, K_{i481}, K_{p482}, K_{i482}, K_{p483}, K_{i483}, K_{p484}, K_{i484}, K_{p485}, K_{i485}, K_{p486}, K_{i486}, K_{p487}, K_{i487}, K_{p488}, K_{i488}, K_{p489}, K_{i489}, K_{p490}, K_{i490}, K_{p491}, K_{i491}, K_{p492}, K_{i492}, K_{p493}, K_{i493}, K_{p494}, K_{i494}, K_{p495}, K_{i495}, K_{p496}, K_{i496}, K_{p497}, K_{i497}, K_{p498}, K_{i498}, K_{p499}, K_{i499}, K_{p500}, K_{i500}, K_{p501}, K_{i501}, K_{p502}, K_{i502}, K_{p503}, K_{i503}, K_{p504}, K_{i504}, K_{p505}, K_{i505}, K_{p506}, K_{i506}, K_{p507}, K_{i507}, K_{p508}, K_{i508}, K_{p509}, K_{i509}, K_{p510}, K_{i510}, K_{p511}, K_{i511}, K_{p512}, K_{i512}, K_{p513}, K_{i513}, K_{p514}, K_{i514}, K_{p515}, K_{i515}, K_{p516}, K_{i516}, K_{p517}, K_{i517}, K_{p518}, K_{i518}, K_{p519}, K_{i519}, K_{p520}, K_{i520}, K_{p521}, K_{i521}, K_{p522}, K_{i522}, K_{p523}, K_{i523}, K_{p524}, K_{i524}, K_{p525}, K_{i525}, K_{p526}, K_{i526}, K_{p527}, K_{i527}, K_{p528}, K_{i528}, K_{p529}, K_{i529}, K_{p530}, K_{i530}, K_{p531}, K_{i531}, K_{p532}, K_{i532}, K_{p533}, K_{i533}, K_{p534}, K_{i534}, K_{p535}, K_{i535}, K_{p536}, K_{i536}, K_{p537}, K_{i537}, K_{p538}, K_{i538}, K_{p539}, K_{i539}, K_{p540}, K_{i540}, K_{p541}, K_{i541}, K_{p542}, K_{i542}, K_{p543}, K_{i543}, K_{p544}, K_{i544}, K_{p545}, K_{i545}, K_{p546}, K_{i546}, K_{p547}, K_{i547}, K_{p548}, K_{i548}, K_{p549}, K_{i549}, K_{p550}, K_{i550}, K_{p551}, K_{i551}, K_{p552}, K_{i552}, K_{p553}, K_{i553}, K_{p554}, K_{i554}, K_{p555}, K_{i555}, K_{p556}, K_{i556}, K_{p557}, K_{i557}, K_{p558}, K_{i558}, K_{p559}, K_{i559}, K_{p560}, K_{i560}, K_{p561}, K_{i561}, K_{p562}, K_{i562}, K_{p563}, K_{i563}, K_{p564}, K_{i564}, K_{p565}, K_{i565}, K_{p566}, K_{i566}, K_{p567}, K_{i567}, K_{p568}, K_{i568}, K_{p569}, K_{i569}, K_{p570}, K_{i570}, K_{p571}, K_{i571}, K_{p572}, K_{i572}, K_{p573}, K_{i573}, K_{p574}, K_{i574}, K_{p575}, K_{i575}, K_{p576}, K_{i576}, K_{p577}, K_{i577}, K_{p578}, K_{i578}, K_{p579}, K_{i579}, K_{p580}, K_{i580}, K_{p581}, K_{i581}, K_{p582}, K_{i582}, K_{p583}, K_{i583}, K_{p584}, K_{i584}, K_{p585}, K_{i585}, K_{p586}, K_{i586}, K_{p587}, K_{i587}, K_{p588}, K_{i588}, K_{p589}, K_{i589}, K_{p590}, K_{i590}, K_{p591}, K_{i591}, K_{p592}, K_{i592}, K_{p593}, K_{i593}, K_{p594}, K_{i594}, K_{p595}, K_{i595}, K_{p596}, K_{i596}, K_{p597}, K_{i597}, K_{p598}, K_{i598}, K_{p599}, K_{i599}, K_{p600}, K_{i600}, K_{p601}, K_{i601}, K_{p602}, K_{i602}, K_{p603}, K_{i603}, K_{p604}, K_{i604}, K_{p605}, K_{i605}, K_{p606}, K_{i606}, K_{p607}, K_{i607}, K_{p608}, K_{i608}, K_{p609}, K_{i609}, K_{p610}, K_{i610}, K_{p611}, K_{i611}, K_{p612}, K_{i612}, K_{p613}, K_{i613}, K_{p614}, K_{i614}, K_{p615}, K_{i615}, K_{p616}, K_{i616}, K_{p617}, K_{i617}, K_{p618}, K_{i618}, K_{p619}, K_{i619}, K_{p620}, K_{i620}, K_{p621}, K_{i621}, K_{p622}, K_{i622}, K_{p623}, K_{i623}, K_{p624}, K_{i624}, K_{p625}, K_{i625}, K_{p626}, K_{i626}, K_{p627}, K_{i627}, K_{p628}, K_{i628}, K_{p629}, K_{i629}, K_{p630}, K_{i630}, K_{p631}, K_{i631}, K_{p632}, K_{i632}, K_{p633}, K_{i633}, K_{p634}, K_{i634}, K_{p635}, K_{i635}, K_{p636}, K_{i636}, K_{p637}, K_{i637}, K_{p638}, K_{i638}, K_{p639}, K_{i639}, K_{p640}, K_{i640}, K_{p641}, K_{i641}, K_{p642}, K_{i642}, K_{p643}, K_{i643}, K_{p644}, K_{i644}, K_{p645}, K_{i645}, K_{p646}, K_{i646}, K_{p647}, K_{i647}, K_{p648}, K_{i648}, K_{p649}, K_{i649}, K_{p650}, K_{i650}, K_{p651}, K_{i651}, K_{p652}, K_{i652}, K_{p653}, K_{i653}, K_{p654}, K_{i654}, K_{p655}, K_{i655}, K_{p656}, K_{i656}, K_{p657}, K_{i657}, K_{p658}, K_{i658}, K_{p659}, K_{i659}, K_{p660}, K_{i660}, K_{p661}, K_{i661}, K_{p662}, K_{i662}, K_{p663}, K_{i663}, K_{p664}, K_{i664}, K_{p665}, K_{i665}, K_{p666}, K_{i666}, K_{p667}, K_{i667}, K_{p668}, K_{i668}, K_{p669}, K_{i669}, K_{p670}, K_{i670}, K_{p671}, K_{i671}, K_{p672}, K_{i672}, K_{p673}, K_{i673}, K_{p674}, K_{i674}, K_{p675}, K_{i675}, K_{p676}, K_{i676}, K_{p677}, K_{i677}, K_{p678}, K_{i678}, K_{p679}, K_{i679}, K_{p680}, K_{i680}, K_{p681}, K_{i681}, K_{p682}, K_{i682}, K_{p683}, K_{i683}, K_{p684}, K_{i684}, K_{p685}, K_{i685}, K_{p686}, K_{i686}, K_{p687}, K_{i687}, K_{p688}, K_{i688}, K_{p689}, K_{i689}, K_{p690}, K_{i690}, K_{p691}, K_{i691}, K_{p692}, K_{i692}, K_{p693}, K_{i693}, K_{p694}, K_{i694}, K_{p695}, K_{i695}, K_{p696}, K_{i696}, K_{p697}, K_{i697}, K_{p698}, K_{i698}, K_{p699}, K_{i699}, K_{p700}, K_{i700}, K_{p701}, K_{i701}, K_{p702}, K_{i702}, K_{p703}, K_{i703}, K_{p704}, K_{i704}, K_{p705}, K_{i705}, K_{p706}, K_{i706}, K_{p707}, K_{i707}, K_{p708}, K_{i708}, K_{p709}, K_{i709}, K_{p710}, K_{i710}, K_{p711}, K_{i711}, K_{p712}, K_{i712}, K_{p713}, K_{i713}, K_{p714}, K_{i714}, K_{p715}, K_{i715}, K_{p716}, K_{i716}, K_{p717}, K_{i717}, K_{p718}, K_{i718}, K_{p719}, K_{i719}, K_{p720}, K_{i720}, K_{p721}, K_{i721}, K_{p722}, K_{i722}, K_{p723}, K_{i723}, K_{p724}, K_{i724}, K_{p725}, K_{i725}, K_{p726}, K_{i726}, K_{p727}, K_{i727}, K_{p728}, K_{i728}, K_{p729}, K_{i729}, K_{p730}, K_{i730}, K_{p731}, K_{i731}, K_{p732}, K_{i732}, K_{p733}, K_{i733}, K_{p734}, K_{i734}, K_{p735}, K_{i735}, K_{p736}, K_{i736}, K_{p737}, K_{i737}, K_{p738}, K_{i738}, K_{p739}, K_{i739}, K_{p740}, K_{i740}, K_{p741}, K_{i741}, K_{p742}, K_{i742}, K_{p743}, K_{i743}, K_{p744}, K_{i744}, K_{p745}, K_{i745}, K_{p746}, K_{i746}, K_{p747}, K_{i747}, K_{p748}, K_{i748}, K_{p749}, K_{i749$

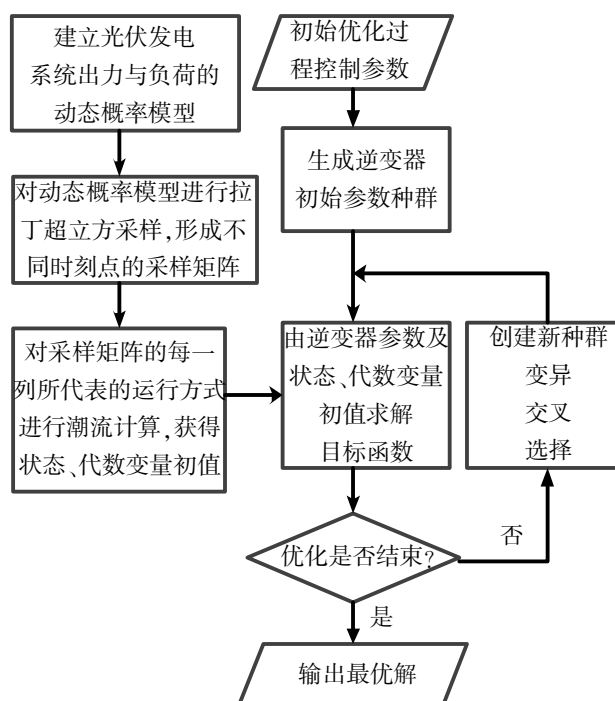


图7 微电网逆变控制器参数优化流程图

Fig. 7 Flow chart of the proposed optimal design approach for inverter controllers in microgrid

的出口电压均为 380 V; 柴油机调速与励磁系统参数见文[21]; 光伏发电与储能系统的等效连接阻抗 $R_{c1}=R_{c2}=0.01 \Omega$, $L_{c1}=L_{c2}=0.20 \text{ mH}$; 线路参数 $R_{\text{Line}1}+jX_{\text{Line}1}=(0.187 \ 8+j0.096 \ 8) \Omega$, $R_{\text{Line}2}+jX_{\text{Line}2}=(0.093 \ 9+j0.048 \ 4) \Omega$, $R_{\text{Line}3}+jX_{\text{Line}3}=(0.281 \ 7+j0.145 \ 2) \Omega$ 。

微分进化算法的控制参数对搜索性能具有很大的影响, 根据多次实验及文[16], 文中选择的控制参数见表 1。储能下垂控制器增益 K_{m2} 、 K_{n2} 及隔直时间常数 $T_{\omega 2}$ 的搜索范围设定为 $[0.01, 5]$, 其余参数的搜索范围设定为 $[0.01, 20]$ 。采用图 13 的计算方法进行逆变控制器参数的优化, 结果见表 2, DE 算法的收敛特性见图 8。

表 1 微分进化算法控制参数

Table 1 Control parameters of DE

参数	数值
种群数量 N_p	50
解空间维数 H	15
最大迭代次数 $G_{\max}$	300
终止迭代次数 G_{inv}	100
微分比例因子 F	0.5
交叉因子 C_R	0.5

由图 8 可见: 经过优化后, 整个时间区间所有特征根实部的最大上界 $\alpha_{m,t}'$ 由 1.542 0 变为 -1.894 3, 这说明在所有可能的运行方式下系统的特征根均具有负实部, 即系统是小信号稳定的。

表 2 逆变控制器参数优化结果

Table 2 The optimal settings of inverter controller

逆变控制器参数	最优值	逆变控制器参数	最优值
K_{p1}	14.86	$T_{\omega 2}$	0.15
K_{i1}	16.18	K_{i2}	0.54
K_{p2}	1.84	K_{i2}	18.25
K_{i2}	20.00	K_{i2}	10.61
K_{p1}	4.86	K_{i2}	20.00
K_{i1}	12.90	K_{p2}	8.70
K_{m2}	0.05	K_{i2}	17.32
K_{n2}	0.22	—	—

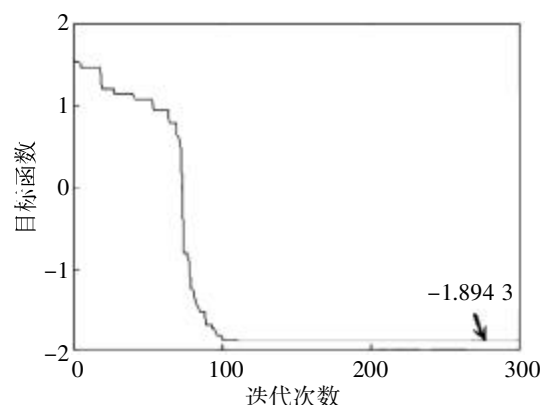


图 8 DE 算法优化收敛特性图

Fig. 8 Objective function convergence curve

系统共有 39 个特征根, 优化后其中 31 个特征根对应的 $\alpha_{m,t}'$ 小于 -20, 说明由其主导的模式在暂态过程中衰减很快, 对微电网的稳定性影响较小; 其余 8 个特征根 (从 $\lambda_{1,t}$ 到 $\lambda_{8,t}$, 共 2 对复根, 4 个实根) 较为接近虚轴, 对系统的稳定性起主导作用。

图 9 给出了逆变控制器参数优化前系统特征根 $\lambda_{1,t}$ 到 $\lambda_{8,t}$ 在 2 种不同运行方式下的分布情况。方式 1、2 分别对应于微电网在 20:00 与 12:00 时刻的运行状态, 其中方式 1 下光伏出力为 0 kW, 负荷为 55 kW; 方式 2 下光伏出力为 24 kW, 负荷为 43.5 kW。从图 9 中可见, 优化前的控制器虽然可以使系统在方式 1 下稳定运行 (所有特征根均位于复平面的左半平面), 但却不能保证系统在方式 2 下也是稳定的 (有两个特征根位于复平面的右半平面)。

经过优化后, 系统特征根 $\lambda_{1,t}$ 到 $\lambda_{8,t}$ 在方式 1、2 下的分布情况见图 10。由图 10 看出, 优化后的控制器能够保证系统在两种运行情况下都很稳定 (两种情况下所有特征根均位于复平面的左半平面)。

为直观描述优化后系统的特征根在整个时间区间的分布情况, 在图 11 中画出了与虚轴距离最近的复根实部 $\alpha_{1,2}$ 的动态概率密度函数, 其余特征根的情况与之类似。

由图 11 可见:

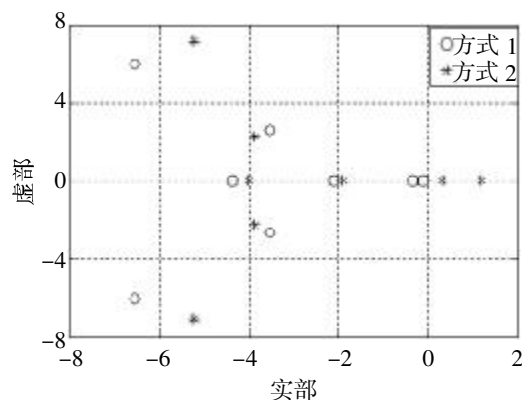


图9 优化前的特征根分布图

Fig. 9 Eigenvalue distribution of microgrid without optimization

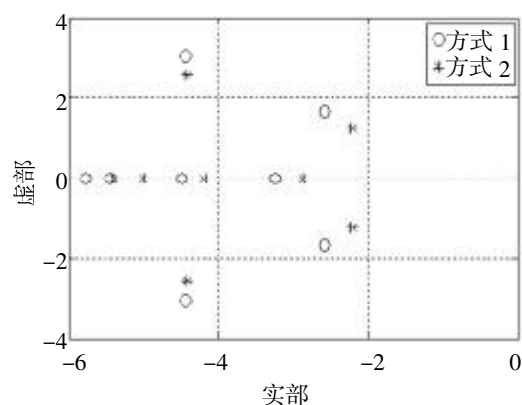
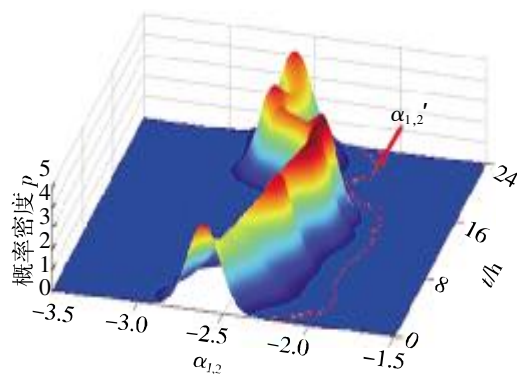


图10 优化后的特征根分布图

Fig. 10 Eigenvalue distribution of microgrid with optimization

图11 $\alpha_{1,2}$ 的动态概率密度函数Fig. 11 Dynamic probabilistic density function of $\alpha_{1,2}$

1) 优化后所有时刻复根实部 $\alpha_{1,2}$ 的上界 $\alpha_{1,2}'$ 均位于虚轴左侧(最大值 $-1.894\ 3$ 对应于 14:00 时刻),说明采用该方法设计的逆变控制器参数可以很好适应微电网运行方式不断变化的情况,鲁棒性较好;

2) 当考虑了光伏发电系统出力与负荷波动在时间轴上的规律性后, $\alpha_{1,2}$ 的波动也具有一定的规律性。在白天光伏发电出力较多的时候, $\alpha_{1,2}$ 的分布较为接近虚轴;而早晚时段,光伏发电出力为零, $\alpha_{1,2}$ 的分布要更加远离虚轴,这说明光伏发电系统的接

入会对系统的小信号稳定性造成不利的影响。

为进一步验证优化参数的有效性,图 12 分别给出 3 种不同运行方式下微电网受扰(扰动设置为 2 s 时,负荷发生 10 kW、5 kvar 的阶跃)后的频率响应图。方式 3~5 分别对应于微电网在 12:00、8:00 与 21:00 的某种运行状态。由图 12 可见,系统在各种运行方式下不仅能够保持小信号稳定,且动态过程的调节时间短、超调量小,在大约 10 s 以内,微网频率最终稳定在 50 Hz,过渡过程中,频率最低仅为 49.5 Hz。

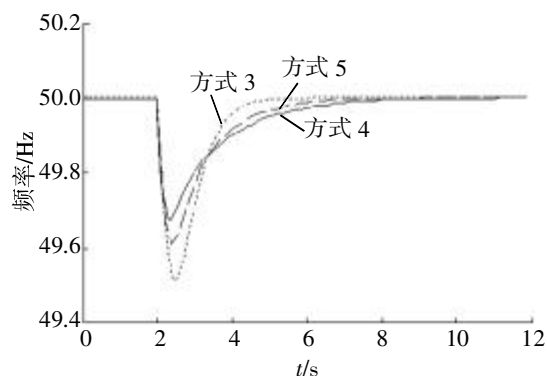


图12 不同运行方式下的微电网频率响应图

Fig. 12 Frequency response of microgrid at different operation conditions

图 13 分别画出了方式 3 下负荷突变后各微电源有功输出功率的变化曲线。由图 13 可见,负荷的突然增加造成了系统频率的下降,储能通过逆变器向微网中快速注入有功功率,有助于维持暂态初期的频率稳定;柴油机通过调速装置同时会增大其有功输出;光伏由于不具备自由调节能力,其输出维持不变。稳态时,计划外负荷功率由柴油机系统承担,储能的输出逐渐恢复到零值。

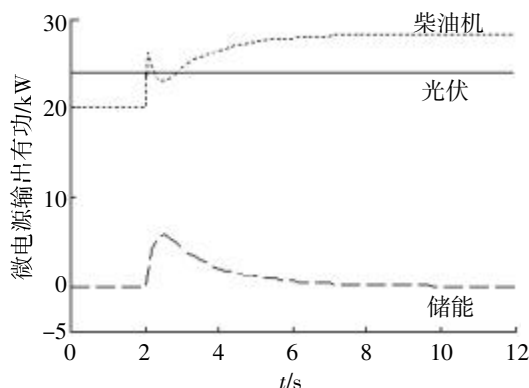


图13 微电源输出有功响应图

Fig. 13 Response of MS power outputs

5 结语

文中首先建立了由柴油机系统、光伏发电系统、储能系统和负荷构成的微电网小信号模型,考虑到光伏发电系统出力和负荷具有的随机性,提出了基

于动态概率特征根分析的微电网逆变控制器参数整体优化方法。仿真结果证明该方法能够较为准确全面地计入微电网运行方式的多样性对特征根分布的影响,由该方法获得的控制器参数鲁棒性好,能够显著改善多运行方式下微电网的稳定性。

参考文献:

- [1] 王成山,杨占刚,王守相,等.微网实验系统结构特征及控制模式分析[J]. 电力系统自动化,2010,34(1):99-105.
WANG Chengshan,YANG Zhangang,WANG Shouxiang, et al. Analysis of structural characteristics and control approaches of experimental microgrid systems[J]. Automation of Electric Power Systems,2010,34(1): 99-105.
- [2] 鲁鸿毅,何奔腾.超级电容器在微型电网中的应用[J]. 电力系统自动化,2009,33(2):87-91.
LU Hongyi,HE Benteng. Application of the super-capacitor in a microgrid[J]. Automation of Electric Power Systems, 2009,33(2): 87-91.
- [3] MERCIER P,CHERKAoui R,oudalov A. Optimizing a battery energy storage system for frequency control application in an isolated power system[J]. IEEE Transactions on Power Systems,2009,24(3): 1469-1477.
- [4] 彭思敏,曹云峰,蔡旭.大型蓄电池储能系统接入微电网方式及控制策略[J]. 电力系统自动化,2011,35(16):38-43.
PENG Simin,CAO Yunfeng,CAI Xu. Control of large scale battery energy storage system interface to microgrid [J]. Automation of Electric Power Systems,2011,35 (16): 38-43.
- [5] KIM J Y,JEON J H,KIM S K,et al. Cooperative control strategy of energy storage system and microsources for stabilizing the microgrid during islanded operation [J]. IEEE Transactions on Power Electronics,2010,25 (12): 3037-3048.
- [6] 沈阳武,彭晓涛,杨军,等.超级电容器储能系统的功率实时控制[J]. 电力自动化设备,2011,31(11):28-32.
SHEN Yangwu,PENG Xiaotao,YANG Jun,et al. Real-time power control of ultracapacitor energy storage system [J]. Electric Power Automation Equipment,2011,31(11): 28-32.
- [7] KATIRAEI F,IRAVANI M R. Power management strategies for a microgrid with multiple distributed generation units[J]. IEEE Transactions on Power Systems,2006,21(4): 1821-1831.
- [8] KATIRAEI F,IRAVANI M R,LEHN P W. Small-signal dynamic model of a micro-grid including conventional and electronically interfaced distributed resources[J]. IET Generation,Transmission & Distribution,2007,1(3): 369-378.
- [9] POGAKU N,PRODANOVIC M,GREEN T C. Modeling, analysis and testing of autonomous operation of an inverter-based microgrid [J]. IEEE Transactions on Power Electronics,2007,22(2): 613-625.
- [10] 张建华,苏玲,刘若溪,等.逆变型分布式电源微网小信号稳定性动态建模分析[J]. 电力系统自动化,2010,34 (22):97-102.
ZHANG Jianhua,SU Ling,LIU Ruoxi,et al. Small-signal dynamic modeling and analysis of a microgrid composed of inverter-interfaced distributed generations[J]. Automation of Electric Power Systems,2010,34(22): 97-102.
- [11] 余昆,曹一家,陈新莺,等.含分布式电源的地区电网动态潮流分析[J]. 中国电机工程学报,2011,31(1):20-25.
YU Kun,CAO Yijia,CHEN Xingying,et al.Dynamic probability power flow of district grid containing distributed generation[J]. Proceedings of the CSEE,2011,31(1):20-25.
- [12] CHUNG C Y,WANG K W,TSE C T,et al. Probabilistic eigenvalue sensitivity analysis and PSS design in multi-machine systems[J]. IEEE Transactions on Power Systems, 2003,18(4): 1439-1445.
- [13] WANG Kewen,TSE C T,TSANG K M. Algorithm for power system dynamic stability studies taking account the variation of load power[C]//Fourth International Conference on Operation and Management.[S.l.]:IEEE,1997: 445-450.
- [14] 李俊芳,张步涵.基于进化算法改进拉丁超立方抽样的概率潮流计算[J]. 中国电机工程学报,2011,31(25):90-96.
LI Junfang,ZHANG Buhan. Probabilistic load flow based on improved Latin hypercube sampling with evolutionary algorithm[J]. Proceedings of the CSEE,2011,31(25): 90-96.
- [15] 于晗,钟志勇,黄杰波,等.采用拉丁超立方采样的电力系统概率潮流计算方法[J]. 电力系统自动化,2009,33 (21):32-35.
YU Han,ZHONG Zhiyong,HUANG Jiebo,et al. A probabilistic load flow calculation method with Latin hypercube sampling[J]. Automation of Electric Power Systems,2009,33 (21): 32-35.
- [16] SHAHEEN H I,RASHED G I,CHENG S J. Optimal location and parameter setting of UPFC for enhancing power system security based on differential evolution algorithm [J]. International Journal of Electrical Power & Energy Systems,2011,33(1): 94-105.
- [17] SHAHEEN H I,RASHED G I,CHENG S J. Application and comparison of computational intelligence techniques for optimal location and parameter setting of UPFC[J]. Engineering Applications of Artificial Intelligence,2010,23 (2): 203-216.
- [18] 刘自发,张建华.一种求解电力经济负荷分配问题的改进微分进化算法[J]. 中国电机工程学报,2008,28(10): 100-105.
LIU Zifa,ZHANG Jianhua. An improved differential evolution algorithm for economic dispatch of power systems [J]. Proceedings of the CSEE,2008,28(10): 100-105.

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参考文献:

- [1] 张 钦,王锡凡,王建学. 电力市场下需求响应研究综述[J]. 电力系统自动化,2008(3): 97-106.
ZHANG Qin,WANG Xifan,WANG Jianxue.Under the electricity market demand response research [J]. Automation of Electric Power Systems 2008(3): 97-106.
- [2] MOGHADDAM M P,ABDOLLAHI A, RASHIDINEJAD M. Flexible demand response programs modeling in competitive electricity markets [J]. Applied Energy,2011,88(9):3257-3269.
- [3] AALAMI H A, MOGHADDAM M P, YOUSEFI G R.Demand response modeling considering interruptible/curtailable loads and capacity market programs [J]. Applied Energy,2010,87(1):243-250.
- [4] CHAOUACHI A,KAMEL R M,ANDOULSI R,et al. Multiobjective intelligent energy management for a microgrid [J]. IEEE Transactions on Industrial Electronics,2013,60(4): 1688-1699.
- [5] MORAIS H,KADAR P,FARIA P,et al. Optimal scheduling of a renewable micro-grid in an isolated load area using mixed-integer linear programming [J]. Renewable Energy,2010,35(1): 151-156.
- [6] 聂江洪,曾伟民.在电力市场中引入电力需求弹性的研究[J]. 电网技术,2008,32(11):84-89.
- NIE Jianghong, ZENG Weimin. Research on introducing electricity demand elasticity into electricity market [J]. Power System Technology,2008,32(11): 84-89.
- [7] VENKATESAN N,SOLANKI J,SOLANKI S K. Demand response model and its effects on voltage profile of a distribution system[C]//IEEE General Meeting Power Engineering Society.[S.l.]:IEEE,2011:1-7.
- [8] CAMPANARI S, MACCHI E. Technical and tariff scenarios effect on microturbine trigenerative applications [J]. Journal of Engineering for Gas Turbines and Power,2004,126(3): 581-589.
- [9] PANDIAN M S,ANWARI M,HUSODO B Y,et al. Efficiency and economics analysis of proton exchange membrane fuel cell[C]//IPEC 2010 Conference Proceedings.[S.l.]:IPEC,2010: 875-880.
- [10] KAHN E. Numerical techniques for analyzing market power in electricity[J]. Electricity Journal,2001,11(6):34-43.

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- [19] 毕大强,葛宝明,王文亮,等.基于钒电池储能系统的风电场并网功率控制[J]. 电力系统自动化,2010,34(13): 72-78.
BI Daqiang,GE Baoming,WANG Wenliang,et al. VRB energy storage system based power control of grid-connected wind farm[J]. Automation of Electric Power Systems,2010,34(13): 72-78.
- [20] 肖朝霞,王成山,王守相.含多微型电源的微网小信号稳定性分析[J]. 电力系统自动化,2009,33(6):81-85.
XIAO Chaoxia,WANG Chengshan,WANG Shouxiang. Small-signal stability analysis of microgrid containing multiple micro sources [J]. Automation of Electric Power Systems,2009,33(6): 81-85.
- [21] KUNDER P. Power system stability and control[M]. New York: McGraw-Hill Inc.,1994.

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