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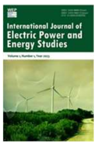

Research on Parameter Design in Realization of LLC Resonant Converter Soft-switching

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ABSTRACT

The soft-switching performance of LLC resonant converter is closely related to the design parameters. The core contradiction lies in the strong coupling characteristics between the parameters of the resonant cavity and the spatial dislocation between the soft-switching range and the optimal efficiency. In this paper, a multi-objective collaborative design framework based on particle swarm optimization algorithm is proposed to solve the problem of performance mutual exclusion caused by parameter coupling, and the global optimal solution of key parameters is searched by building a fitness function of joint optimization of efficiency, gain bandwidth and soft switching range. In order to solve the problem of limited soft switching range under light load and wide input voltage conditions, an improved genetic algorithm is introduced to establish a gradient search mechanism for soft switching boundary constraints, which can expand the operating range of zero voltage switching while maintaining the efficiency balance. The research results reveal the inherent relationship between the static parameter system and the adaptability of dynamic conditions, and provide a systematic design paradigm for the engineering realization of high reliability LLC converters.

KEYWORDS

Parameter Design; LLC Resonant Converter; Soft-switching.

1. INTRODUCTION

With the development of power electronics technology in the field of high efficiency power conversion, LLC resonant converter has become the core topology of high-power scenarios such as data center power supply and electric vehicle charging pile because of its excellent soft switching performance and wide input range adaptability [1]. The converter can significantly reduce the high frequency switching loss through the zero voltage switching characteristics of the resonant cavity, and can theoretically break through the efficiency bottleneck of the traditional hard-switching converter. However, in practical engineering design, the parameter system composed of excitation inductance, resonant inductance and resonant capacitance of transformer has strong coupling characteristics, which greatly limits the design freedom. This non-linear relationship between parameters often leads to conflicting design objectives: excessive pursuit of a wide voltage gain range will sacrifice the soft-switching capability at light load, while ensuring zero-voltage turn-on at full load will reduce the voltage regulation margin.

The current engineering practice generally relies on trial-and-error method or empirical formula for parameter selection, which lacks a systematic optimization framework [2].

In recent years, although some studies have tried to use numerical algorithms to optimize parameters, most of the schemes only seek local optimization for a single objective, and fail to effectively solve the optimal compromise problem with multiple constraints. For example, the linkage effect between the resonant frequency and the load change makes it difficult for the fixed parameter system to maintain the soft switching state in the whole working condition, and the dynamic adjustment of the switching frequency brings the secondary problem of increasing the control complexity. This limitation is essentially due to the inherent contradiction between the multi-dimension of the target and the boundary of the constraint in the design of the resonance parameters.

This paper focuses on the parameter design problems in the realization of LLC resonant converter soft-switching, focusing on two typical problems: the effect of parameter coupling and the limitation of soft-switching range. A collaborative design strategy based on intelligent optimization algorithm is proposed by establishing the objective conflict mapping relationship of key parameters.

2. PROBLEMS AND SOLUTIONS OF PARAMETER COUPLING

2.1. Parameter Coupling

In the parameter design system of the LLC resonant converter, the core parameter group composed of the transformer magnetizing inductance L_m, resonant inductance Lr and resonant capacitor C_r exhibits significant non-linear coupling characteristics. This coupling effect is specifically manifested as a mutually exclusive conflict of key performance indicators. When designers attempt to broaden the voltage gain range of the converter by adjusting the inductance ratio $K= L_m/L_r$, the soft-switching ability under light-load conditions will be weakened simultaneously. The physical mechanism behind this is that an increase in the K value suppresses the equivalent impedance of the resonant cavity under low-load conditions, causing the amplitude of the magnetizing current to be insufficient to complete the charging and discharging process of the parasitic capacitance of the switching tube within the dead-time, forcing some switching tubes to exit the zero-voltage turn-on state. Conversely, if the K value is overly reduced to enhance the soft-switching ability under light-load conditions, it will trigger the risk of magnetizing current saturation under heavy-load conditions and significantly compress the voltage regulation freedom [3].

The introduction of the quality factor Q further exacerbates the complexity of parameter design. The Q value reflects the energy transfer efficiency of the resonant cavity, and its value is jointly determined by Lr, C_r and the load resistance. A high-Q design can improve the power conversion efficiency near the resonant frequency f_r, but it causes the voltage-gain curve to become steep near the resonant peak. This non-linear response characteristic makes the operating point prone to drift due to load disturbances. In mild cases, it causes output voltage instability, and in severe cases, it triggers the switching frequency to cross into the non-soft-switching region. Especially when $f_s < f_r$, (under-resonant operating region), the phase lag of the resonant current forces the switching tube to turn on after the forward current flows through the body diode. At this time, if the Q value is set too high, a slight attenuation of the current amplitude will lead to the failure of zero-voltage switching.

An even more intractable contradiction lies in the mismatch between the soft-switching boundary conditions and the optimal efficiency point. Theoretical analysis shows that the reliable realization of zero-voltage switching requires the converter to operate in the current-phase-lag region, while the peak of the system efficiency usually occurs near the purely resistive operating point where $f_s = f_r$. This spatial misalignment forces designers to make compromises within the control range of f_s. Shortening the downward-adjustment range of the switching frequency can maintain high efficiency, but sacrifices the voltage-regulation ability when the input voltage surges. Excessively expanding the adjustment range of f_s can enhance voltage adaptability, but inevitably pushes some operating points into the low-efficiency region. Existing design methods based on fundamental-wave approximation ultimately result in parameter design results deviating from the expected goals because they neglect non-linear factors such as dead-time delay and device junction capacitance.

2.2. Parameter Coupling Optimization based on Particle Swarm Optimization

Aiming at the strong coupling conflicts among the inductance ratio K, quality factor Q and resonant frequency f_r in the LLC resonant converter, the traditional trial-and-error method is difficult to achieve the global optimal solution. The Particle Swarm Optimization (PSO) algorithm, through the swarm intelligence search mechanism, transforms the parameter design into a multi-objective optimization problem [4]. Taking the resonant cavity efficiency η, voltage gain bandwidth ΔG and soft-switching range Δf_{zvs} as objective functions, a quantitative model of parameter coupling conflicts is established. The core of it lies in designing the fitness function F, which comprehensively represents the trade-off of multi-objective performance:

$$F = \alpha \cdot \eta + \beta \cdot \Delta G + \gamma \cdot \Delta f_{zvs}$$

Among them, the weight coefficients α, β, γ are adjusted according to the application scenarios (for example, for the power supply of data centers, efficiency is emphasized with $\alpha = 0.5$, and for photovoltaic inverters, gain bandwidth is emphasized with $\beta = 0.4$. The particle position vector $X_i = [K_i, Q_i, f_{r,i}]$ represents a set of parameter combinations. The position and velocity are updated iteratively as follows:

$$V_i^{t+1} = \omega V_i^t + c_1 r_1 (P_{best} - X_i^t) + c_2 r_2 (G_{best} - X_i^t)$$
$$X_i^{t+1} = X_i^t + V_i^{t+1}$$

In the above equations, ω is the inertia weight, which linearly decreases with the number of iterations to balance the global exploration and local exploitation capabilities; c_1 *and* c_2 are learning factors; P_{best} *and* G_{best} are the individual and global historical optimal solutions respectively. The constraint conditions need to incorporate the physical limitations of the resonant cavity.

The first constraint is the soft-switching boundary, ensuring that when $f_s < f_r$, the peak value of the resonant current $I_{peak} > I_{zvs,min}$; the second constraint is to avoid magnetic saturation, where the magnetizing current $I_m < 0.8 \cdot I_{sat}$; the third constraint is the voltage withstand limit of the capacitor, with the resonant capacitor voltage $V_{Cr} < 0.9 \cdot V_{rated}$.

The following is a simplified code implementation (in Python) of the core calculation logic of PSO:

```
import numpy as np
def pso_optimization():
    particles = np.random.uniform(low=[1.5, 0.3, 80e3], high=[6.0, 0.7, 200e3], size=(50, 3))  [K, Q, fr]
    velocities = np.zeros_like(particles)
    p_best = particles.copy()
    g_best = particles[0]
    for epoch in range(100):
        for i in range(len(particles)):
            K, Q, fr = particles[i]
            efficiency = calc_efficiency(K, Q, fr)
```

```
            gain_bandwidth = calc_gain_bandwidth(K, Q)
            zvs_range = calc_zvs_range(K, fr)
            fitness = 0.5 * efficiency + 0.3 * gain_bandwidth + 0.2 * zvs_range
            if fitness > evaluate(p_best[i]):
                p_best[i] = particles[i]
            if fitness > evaluate(g_best):
                g_best = particles[i]
            w = 0.9-0.5 * epoch / 100
            r1, r2 = np.random.rand(2)
            velocities[i] = w * velocities[i] + 2 * r1 * (p_best[i]-particles[i]) + 2 * r2 * (g_best-particles[i])
            particles[i] += velocities[i]
            particles[i] = np.clip(particles[i], [1.5, 0.3, 80e3], [6.0, 0.7, 200e3])
    return g_best
```

3. LIMITATIONS AND SOLUTIONS OF SOFT SWITCHING

3.1. Soft Switch Limitations

Although the soft-switching performance of the LLC resonant converter is its core advantage, it has significant limitations in wide-operating-condition applications. The primary contradiction lies in the spatial misalignment between the soft-switching maintenance range and the optimal efficiency point. The reliable realization of zero-voltage switching requires operation in the under-resonant region where the switching frequency is lower than the resonant frequency. At this time, the phase lag of the resonant current ensures that the switching tube turns on during the conduction of the body diode. However, the peak of the system efficiency is concentrated near the resistive operating point where the switching frequency is equal to the resonant frequency. This misalignment forces designers to compromise between efficiency and the soft-switching range [5]. Excessive pursuit of efficiency will compress the input voltage adjustment margin, while expanding the soft-switching range requires pushing some operating points into the low-efficiency region.

Load fluctuations further exacerbate the instability of soft-switching. Under light-load conditions, the attenuation of the resonant current amplitude leads to insufficient magnetizing energy, making it impossible to complete the charging and discharging process of the parasitic capacitance of the switching tube within the dead-time, forcing some switching tubes to exit the zero-voltage turn-on state. Especially in designs with an overly high inductance ratio, the light-load resonant current may be lower than the charging threshold of the parasitic capacitance, directly causing hard-switching losses. Under heavy-load conditions, although the current amplitude is sufficient, the excessive current stress increases the risk of core saturation. If the operating frequency accidentally falls into the capacitive region, it will cause diode reverse-recovery losses and voltage spikes.

An overly wide input voltage variation range is another key constraint. When the input voltage drops suddenly, the converter needs to reduce the switching frequency to maintain the voltage gain, which may cause the operating point to enter the deep under-resonant region. At this time, the excessive lag of the resonant current will break the zero-voltage switching conditions. When the input voltage surges suddenly, the frequency is forced to increase to the over-resonant region. Although zero-voltage switching can be maintained, the excessively high frequency leads to a sharp increase in core losses. The parameter discreteness of the multi-phase parallel system also threatens the homogeneity of soft-switching. Slight differences in the values of resonant-cavity components will result in uneven current distribution among the phases. Some branches lose their soft-switching ability due to an overly low load rate, while other branches face a sharp increase in thermal stress due to overloading. This imbalance is particularly prominent during dynamic load switching and may trigger a chain reaction of local failures.

These limitations jointly reveal the essential contradiction in the realization of LLC soft-switching: the static parameter system is difficult to dynamically adapt to multi-dimensional disturbances of input voltage, load, and temperature, ultimately restricting the reliability of the converter in wide-range application scenarios.

3.2. Soft-Switching Range Expansion based on Genetic Algorithm

Aiming at the problem that the soft-switching range of the LLC resonant converter is limited under light-load and wide-input-voltage operating conditions, traditional parameter design methods are difficult to reconcile the spatial conflict between the zero-voltage-switching (ZVS) boundary and the peak efficiency. The Genetic Algorithm (GA), by simulating the biological evolution mechanism, transforms the expansion of the soft-switching range into a multi-constraint optimization problem. Its core lies in constructing an objective function that takes into account both the ZVS maintenance ability and efficiency balance. Define the fitness function F as:

$$F = \eta \cdot \exp\left(-\lambda \cdot \max\left(\theta, I_{zvs,min} - I_{peak}\right)\right)$$

where η is the converter efficiency, I_{peak} is the peak value of the resonant current, $I_{zvs,min}$ is the minimum current threshold required to maintain ZVS, and λ is the penalty weight coefficient. This function transforms the current boundary condition into a continuously optimizable soft constraint through the exponential penalty term, ensuring that the algorithm simultaneously expands the ZVS operating range near the optimal efficiency solution.

The algorithm implementation adopts a real-number coding scheme, and the individual gene is represented as a three-dimensional vector $X = [L_m, C_r, f_r]$, which directly maps the core parameters of the resonant cavity. To overcome the randomness defect of the traditional crossover operator, an improved linear crossover strategy is introduced: if the fitness of the parental individual X_a is better than that of X_b, the generation of the offspring follows:

$$X_{child} = X_\alpha + \alpha \cdot (X_b - X_a) + \beta \cdot D$$

where α∈[0,1] is the directional crossover coefficient, D is the gradient-direction vector based on the ZVS boundary, and β is the adaptive step size. This operation enables the offspring to inherit the characteristics of the superior parent while exploring along the gradient direction of the soft-switching constraint boundary, effectively avoiding the invalid solution space. The mutation operation uses Gaussian perturbation, but only acts on the L_m and C_r dimensions to maintain the stability of the resonant frequency. The following is the core iterative logic of the improved genetic algorithm (Python):

```
def ga_zvs_optimize():
    population = initialize_population()
```

```
for generation in range(MAX_GEN):
    fitness = [fitness_function(ind) for ind in population]
    elite = select_elite(population, fitness)
    offspring = []
    while len(offspring) < OFFSPRING_SIZE:
        parents = tournament_selection(population, fitness)
        if random.random() < P_CROSSOVER:
            child = linear_crossover(parents[0], parents[1])
            child = gaussian_mutation(child)
    population = elite + offspring
return optimal_solution
```

4. CONCLUSION

The parameter design of the LLC resonant converter essentially aims to address the dynamic balance of multi-dimensional performance goals. The non-linear coupling characteristics of the resonant cavity parameters result in inherent conflicts among the voltage gain range, soft-switching ability under light load, and peak efficiency. Traditional fundamental-wave approximation models are difficult to achieve precise design due to the neglect of non-linear factors. In this paper, the particle swarm algorithm is used to transform the parameter coupling conflicts into a multi-objective optimization problem, approaching the global optimal solution set within the solution space. Meanwhile, the directional evolution mechanism of the genetic algorithm is utilized to reconstruct the soft-switching constraint boundary, significantly enhancing the zero-voltage-switching robustness of the converter under wide input voltage and load fluctuations. The collaborative application of the two intelligent optimization algorithms breaks through the limitations of the static parameter system in adapting to dynamic operating conditions, forming a design method that takes into account both theoretical rigor and engineering practicality. Future research could further explore the parameter adaptive regulation mechanism to cope with more complex multi-physical-field coupling challenges.

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