

Simple Control Method Tames Flux Saturation In High-Frequency Transformer-Link Full-Bridge DC-DC Converters

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The high-frequency transformer-link dc-dc converter is the preferred topology for low- and medium-power plasma-cutting applications since it is compact, light and provides good dynamic response. Galvanic isolation, which is a necessary requirement of this application, is obtained using a light-weight, high-frequency transformer that is inexpensive and compact in contrast to the bulky and heavy line-frequency version.

However, such systems suffer from the problem of transformer-core flux saturation. Flux saturation in the transformer core causes a rapid increase in its magnetizing current and corresponding converter switch currents [1]. This further leads to an abnormal increase in converter switch loss and electromagnetic (EM) noise. Flux saturation can cause shutdown of a power supply unit by triggering the supply's overcurrent protection. In some extreme cases, a unit may even fail catastrophically [1]. These types of problems are especially unacceptable in large plasma-cutting system applications, where unexpected production stoppages due to such occurrences can be very costly to the customer.

The main cause of transformer flux saturation is duty-cycle asymmetry between the converter switches leading to flux imbalance and its subsequent buildup in one direction or the other. This phenomenon, which is also known as flux walking, can occur as a result of steady-state factors like unequal switch duty-cycle ratios, gate-drive circuit time delays, switch transient time tolerances, and unequal switch voltage drops. Flux saturation can also occur due to dynamic changes in the switch duty-cycle ratios such as during unit startup and line and load disturbances.

Several solutions have been proposed to address this problem. Reference [2] analyzes the use of a series capacitor with the transformer primary winding. Reference [3] mentions the use of an air-gapped core transformer with switch-current-balancing control to prevent flux saturation. Reference [4] proposes direct flux sensing using an air-gapped core transformer with appropriate modification of the converter switch signals. Reference [5] suggests a control method that changes the switch duty cycle in steps during transient situations. Further, the transformer core is designed to handle twice the rated steady-state peak-flux excursion.

However, all these solutions have their disadvantages. For instance, the series capacitor approach cannot be considered for power levels greater than 2 to 3 kW [2]. Further, it cannot prevent flux saturation due to switch duty-cycle asymmetry [2]. Introducing an air gap in the transformer core only delays the onset of flux saturation, while increasing the magnetizing current and switch loss [3]. Similarly, there is cross-coupling between the flux controller and the main control loop in the method described in reference [4] resulting in a suboptimal system dynamic response. The method proposed in reference [5] increases the size and cost of the transformer and degrades the system dynamic response.

The simple method of transformer-flux control proposed here overcomes many of the disadvantages of the current approaches. The proposed method maintains tight control of the transformer flux by steering the PWM output signal to the appropriate converter switch without affecting the main control loop. This enables full utilization of the transformer core without compromising the system dynamic response. Furthermore, it can be retrofitted into an existing power supply with minimal impact on its circuitry. Since the main control loop is left unaffected, this method can be used in a variety of applications, whether voltage or current controlled and in converter topologies like the push-pull as well as the full bridge.

This article begins with a review of the conventional full-bridge-converter plasma-cutting system, and then discusses the mechanics of transformer flux saturation, explaining both its causes and effects. With that as background, the principle of operation of the proposed control method and its circuit implementation are described.

Conventional DC-DC Converter-Based Plasma-Cutting Power Supply

Power Circuit Description

The schematic diagram of a typical plasma-cutting full-bridge dc-dc converter power circuit is shown in Fig. 1. Here, the power circuit consists of a front-end three-phase diode bridge connected to a dc capacitor, C1. In the typical application, the input ac terminals are connected to a three-phase 60-Hz/480-V line through a three-pole

manual switch. The soft-start circuit associated with the dc capacitor charging during unit startup is not shown for the sake of simplicity.

A full-bridge circuit consisting of switches Q1 through Q4 with their corresponding anti-parallel diodes D1 through D4 is connected across the dc bus. T1 is a high-frequency transformer providing galvanic isolation between the incoming line and the plasma torch load. The T1 primary winding is connected across the full-bridge circuit ac terminals, while its secondary voltage is appropriately stepped down, full-wave rectified and connected to the torch load through an output filter inductor, L1.

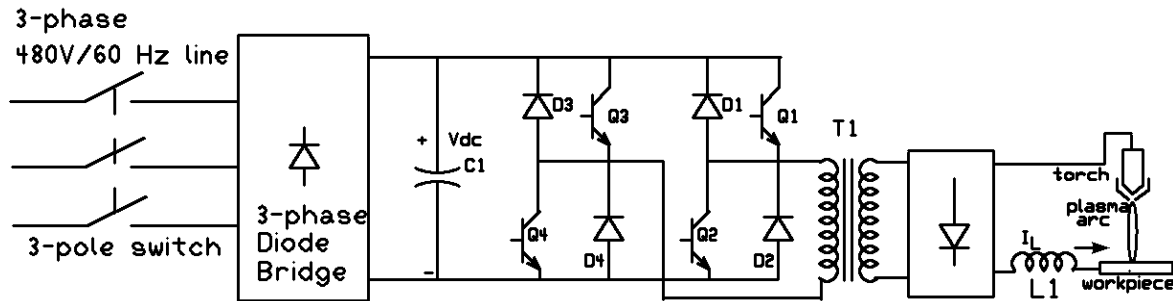


Fig. 1. Full-bridge dc-dc converter power circuit.

Conventional PWM Average-Current-Control Circuit

Fig. 2 shows the schematic block diagram of a conventional PWM average-current-control circuit implemented using analog circuit blocks. In a plasma-cutting application, the desired current reference, I_{ref} , is selected based on the type of material to be cut and its thickness. The control circuit alternately operates switch pairs Q1-Q4 and Q2-Q3 and adjusts their duty-cycle ratios using the pulse width modulation (PWM) average-current-mode control method [6].

The error controller is usually of the proportional-integral-derivative (PID) type. The converter switching frequency for power levels in the 5- to 30-kW range is generally in the 15- to 100-kHz range and is determined by the carrier wave frequency.

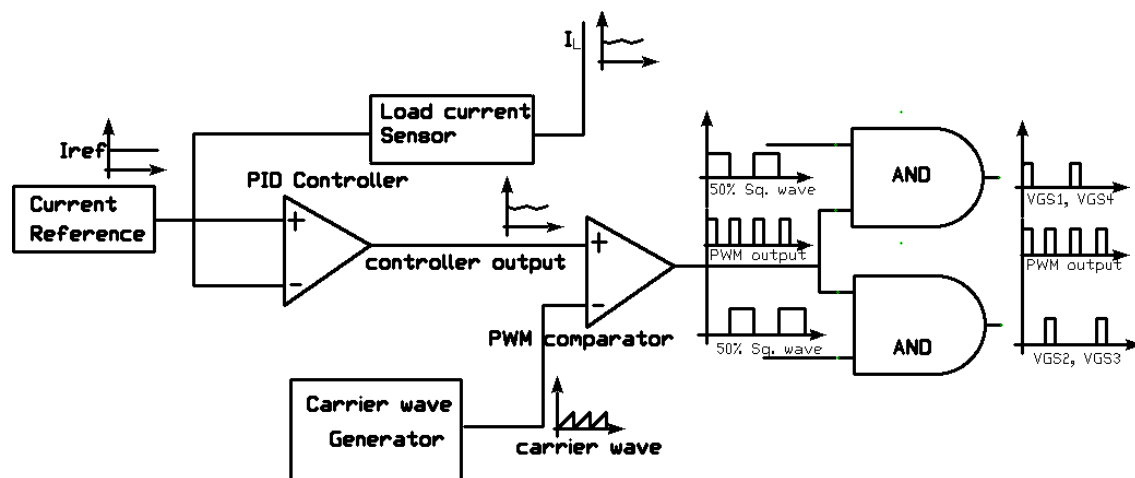


Fig. 2. Full-bridge dc-dc converter control circuit.

Transformer-Core Flux-Saturation Problem

Fig. 3 shows a graph of the main transformer flux ϕ vs. magnetizing current I_m with its safe operating area marked by dotted lines. The switch pairs Q1-Q4 and Q2-Q3 operate alternately to maintain the flux value within this region. In an ideal steady-state situation, symmetric operation of the switches results in equal and opposite transitions of ϕ around the origin (shown by the blue lines in Fig. 3). This results in maximum utilization of the transformer core.

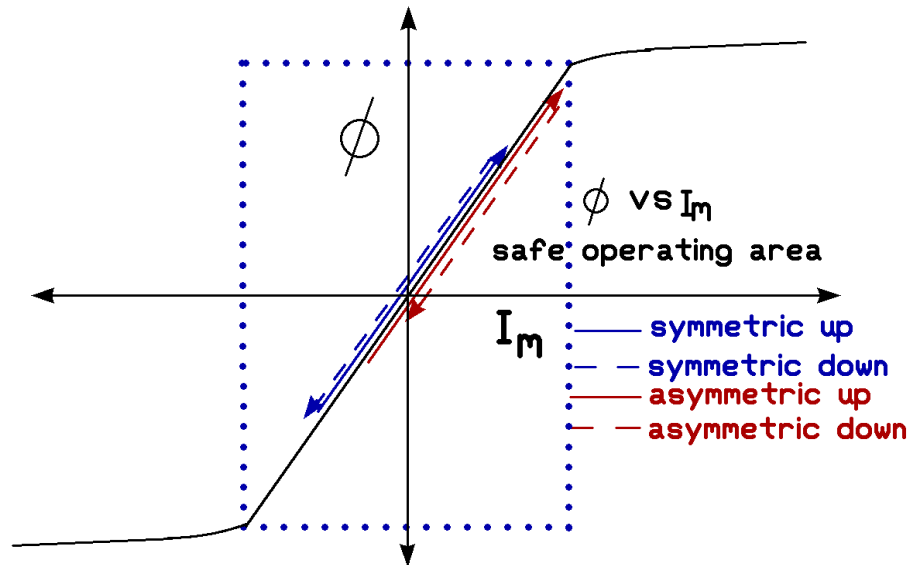


Fig. 3. ϕ vs. I_m relationship.

However, consider the case shown in Fig. 4, where the duty-cycle ratio of switch pair Q1-Q4 is more than that of Q2-Q3. Here, the upward transition of the flux due to Q1 and Q4 is more than its corresponding downward transition due to Q2 and Q3. This results in a net positive flux value at the end of the current switching cycle (shown by the red lines in Fig. 3), which becomes the starting point for the next switching cycle.

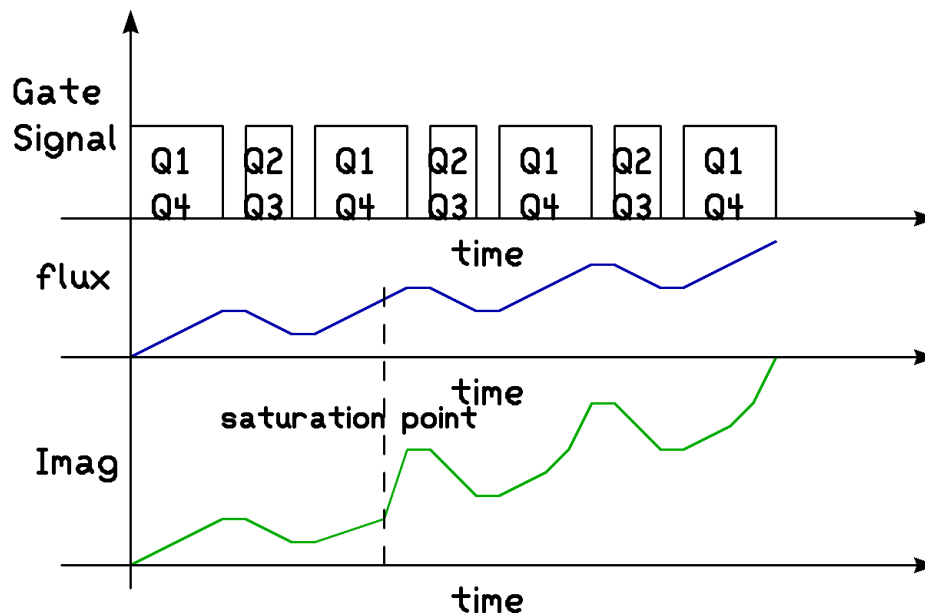


Fig. 4 Flux saturation buildup due to flux walking.

This imbalance leads to ratcheting of the transformer flux up the ϕ - I_m curve with subsequent switching cycles, a phenomenon known as flux walking. The resulting cycle-by-cycle buildup of I_m is shown Fig. 4.

Consequences of transformer flux saturation: The rapid increase in I_m as ϕ enters the saturation region increases switch and transformer losses [2]. Further, it can cause abrupt tripping of the unit's overcurrent protection or even catastrophic unit failure under extreme circumstances, leading to unexpected production stoppages and the associated economic loss to the customer.

Reasons for transformer flux saturation: Transformer flux saturation occurs as a result of flux imbalance due to asymmetric operation between the converter switches [1]. This can be due to steady-state factors like unequal

switch duty-cycle ratios and gate-drive-circuit time delays, switch-transient-time tolerances, and unequal switch and rectifier diode-voltage drops.

Flux saturation can also occur as a result of cycle-by-cycle changes in the switch duty ratios as could happen during unit startup or under line and load variations. For example, in a plasma-cutting application, arc load changes occur during ramp up and ramp down situations at the beginning and end of every cut cycle.

Proposed Transformer-Flux-Saturation Control Method

A schematic block diagram of the proposed control method, overlaid on top of the conventional current-control circuit is shown in Fig. 5. Here, the conventional portion (shown in blue) has already been described in the preceding section. The proposed flux-saturation controller (shown in black) steers the PWM output from Q1 and Q4 to Q2 and Q3 (or vice-versa) at the instant of flux saturation. It operates as follows:

Step 1. Steer the PWM output to say, Q1 and Q4, while monitoring flux ϕ till it reaches its maximum value.

Step 2. Switch off Q1 and Q4 at that instant and direct the remainder of the PWM output to Q2 and Q3 to reverse the flux direction. Continue to monitor ϕ until it reaches its minimum value.

Step 3. Go back to Step 1.

Thus, tight control of ϕ is maintained without compromising the load-current control. This is because the load current, I_L , is determined only by the overall PWM duty-cycle value, which remains unchanged. Thus, both ϕ and I_L are controlled independently without any undesirable cross-coupling between the two.

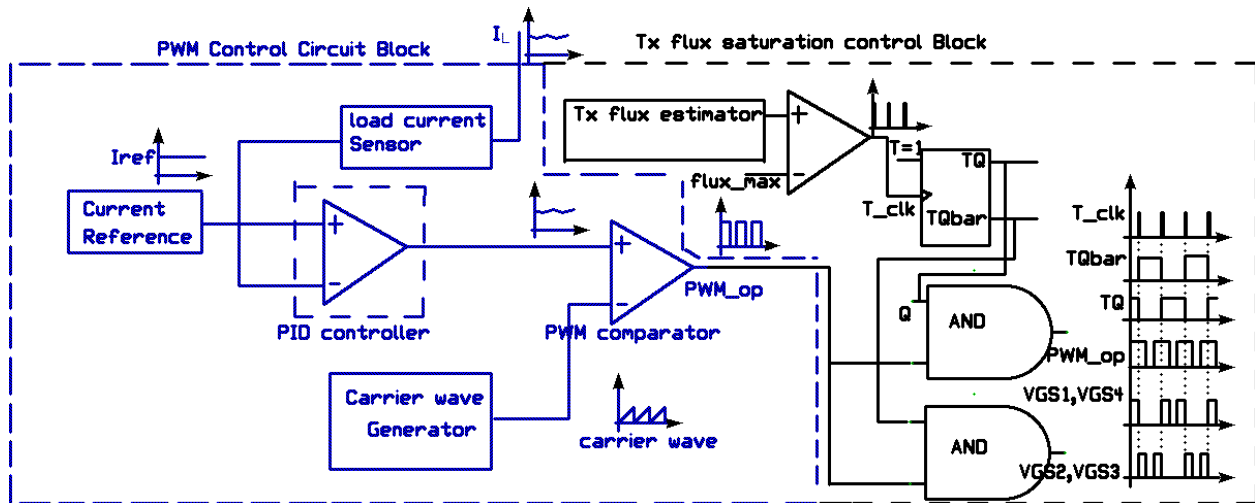


Fig. 5. Dc-dc converter control circuit with proposed flux-saturation control method.

The flux-saturation controller is implemented using a flux-estimator block, a flux comparator and a switch-steering circuit made up of a T flip-flop (T-FF) and a couple of AND gates.

The function of the flux estimator block is to monitor the flux ϕ in real-time. This is typically implemented by sensing the transformer primary and secondary currents using current transformer (CT) or Hall current sensors. I_m is then calculated from these quantities and the transformer turns ratio and used as an indirect measurement of ϕ in the flux comparator block.

The flux comparator compares I_m with a reference that represents the saturated-flux value. It generates a clock pulse for the switch-steering circuit on detection of flux saturation.

The switch-steering circuit uses the flux-saturation detection signal to reverse the flux direction by steering the PWM signal from Q1 and Q4 to Q2 and Q3 (or vice-versa). It is implemented using a T-FF and a couple of dual input AND gates. The flux comparator clocks the T-FF and updates the switch steering flag. The AND gate accordingly steers the PWM signal to the appropriate switch pair based on the T-FF output.

Fig. 6 shows waveforms of the various parameters to illustrate operation of the flux saturation controller. Here, Q1 and Q4 (or Q2 and Q3) consists of two consecutive fractional PWM pulses. This is because flux saturation is

detected in the midst of a PWM pulse. The flux saturation detection and steering flip-flop outputs are also shown here. Alternatively, the switch pairs can switch multiple times if multiple flux-saturation events are detected in one PWM pulse period. Thus, there are three vital differences in the switch signals between the proposed and conventional control methods. These differences are summarized in the table.

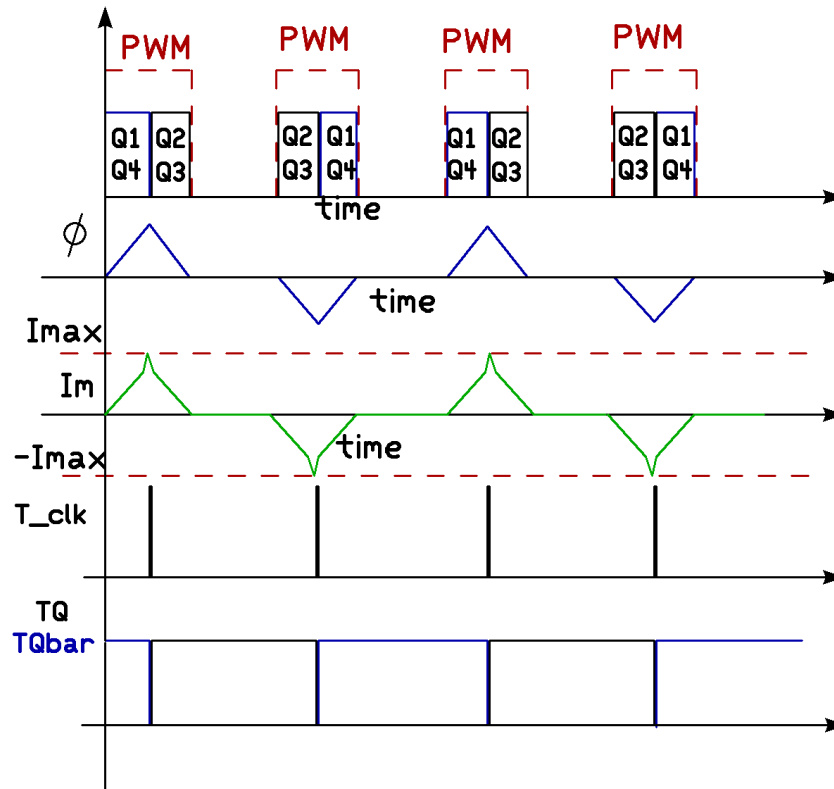


Fig. 6 Waveforms for proposed flux-saturation control method.

Table. Switch-signal differences between proposed and conventional methods of flux-saturation control.

Parameter	Proposed Control Method	Conventional Control Method
Instant of steering signal transfer	Takes place anywhere during a PWM pulse signal at the instant of flux saturation	Takes place at the end of the carrier wave signal
Number of switch pulses per carrier frequency cycle	Consists of whole and/or fractional PWM pulses per switching period	One whole PWM pulse signal per carrier cycle
Switching frequency f_s	Equal to or greater than the carrier frequency f_c and can vary with load and line operating conditions	Constant at f_c throughout the entire operating range.

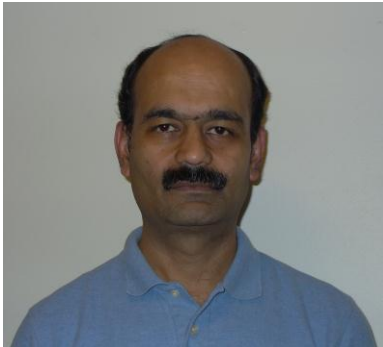
Summary

The proposed method controls the transformer flux by steering the PWM output signal to the appropriate converter switch, without compromising the dynamics of the main control loop. This enables full utilization of the transformer core and correspondingly reduces its size and weight. Furthermore, it can be retro-fitted into an existing power supply with minimal modifications to its circuitry. The next step in describing this transformer-flux control method is to verify its operation by means of simulation and experiment. These results will be presented in a future article.

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About The Author



Girish R. Kamath graduated with a Masters degree in 1996 and a Ph. D in Electrical Engineering from the University of Minnesota in 1998. Since then Girish has been working in the U.S. motor drives and plasma cutting industries. He also has work experience in the Indian power electronics industry, in the area of high-frequency power conversion for UPS applications. Girish currently designs power electronic systems and controls for plasma-cutting power supplies. His main areas of interest are the multi-physics modeling approach to power component design, high-voltage circuits, and digital control.