

Evolution of IC Switching Voltage Regulator

Abstract. To satisfy the fast voltage regulation and low input harmonic current distortion, a voltage regulator and a power factor correction (PFC) pre-regulator need to be existed. Cascading the voltage regulator with the PFC pre-regulator is the simplest way to implement the switching voltage regulator. The voltage regulator and PFC pre-regulator is processed the input power for switching regulator serially. The switching regulators efficiency has confirmed deteriorate. The requirement of the harmonic emission has been satisfied by the various types of the non-cascading PFC switching regulators. In this paper, the evolution of the switching regulator and various types of the non-cascading PFC switching regulator is discussed and the design of implementation of different output power levels for two types of non-cascading PFC switching regulator is presented.

Streszczenie. Do regulacji napięcia skuteczną metodą jest kaskadowe połączenie regulatorów napięcia i układów korekcji współczynnika mocy PFC. W artykule omówiono ewolucję różnych przełączalnych regulatorów napięcia. Przedstawiono też projekt i zastosowanie dwóch rodzajów regulatorów nie połączonych kaskadowo. **Ewolucja przełączalnych regulatorów napięcia.**

Keywords: CMOS, Input harmonic current, PFC, pre-regulator, voltage regulator

Słowa kluczowe: CMOS, regulator napięcia, korektor współczynnika mocy

Introduction

In modern world, integrated circuit (IC) is an advanced electric circuit by patterned diffusion of trace elements into the thin surface of a semiconductor material. Today all electronic equipment is used IC, which has revolutionized the world of electronics [1-3]. Due to advent, of complex metal oxide semiconductor (CMOS) technology, semiconductor devices pervade in every discipline of engineering. Therefore, voltage regulators become core components in various applications especially in radio frequency identification (RFID) appliances [4-6]. To store energy in any kind of storage devices like inductor, transformer or capacitor, which are required to transfer energy from the input to output in a packets over a low resistance switch. All these switching voltage regulators are ICs. Hence, a feedback circuitry is needed to regulate the transferred energy and to maintain a constant voltage within the load limits of the circuit.

Conventional, AC/DC converters draw a non-sinusoidal current from the mains, which are harmonic currents. However, the main disadvantage of this harmonic current is: its generate harmonic voltages that can interfere with electrical equipment. In addition, harmonic currents cause a lot of trouble to the power system. Three-phase power system of the harmonic currents has been highlighted by Steinmetz [7-8]. Texas A&M University found the effects of the excessive harmonic currents, which resides inside the neutral conductor. 133.1% of the ratio for the neutral current to the phase current has been found. Triplen harmonic current has form the neutral current in high value. Therefore, the dominant load from a single-phase power electronic load creates high neutral current [9]. Harmonic current are the sources for power electronic loads. For instance, electrical appliances, battery chargers, personal computers and others contain the sources of the harmonic current. Total harmonic distortion (THD) for the current will evaluate and measure the distortion periodic current waveform. The ratio of the root-means square (rms) value of current waveform to the rms fundamental magnitude defined by the THD, which can be written as:

$$(1) \quad THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1}$$

Power factor correction (PFC) is the required circuit in any off-line power supply system as the circuit can reduce the harmonic current. Input current controlling and filtering are the two techniques to achieve PFC into an off-line

power supply system. Both techniques have been used by Redl in an off-line power supply system [10]. Active filter circuits and passive filter circuits are the filtering techniques [11-12].

Several researches have been done to improve and to reduce the harmonic current level. Each of the proposed method is replaced or improved by other researchers throughout all these years. Therefore, it is obvious that there is evolution for improving the harmonic current and efficiency. In this paper, various number of the design is reviewed according to the outcomes and a summary of all the reviewed researches are presented at the end of this paper with further discussion.

Background

By using a suitable control circuitry, dc-dc converter can achieve the input current controlling techniques [13]. Tse has been investigated the theory to achieve PFC by using switching regulators and voltage regulation [14]. Singh et al. include the control approaches to improve power factor converters [15-16]. Fernandez et al. suggest how to select a PFC solution for low and medium power single-phase switching regulators [17]. In order to satisfy an efficient power conversion, PFC circuits have been drawn with imperfect sinusoidal input current, which has been studied by Garcia et al. [18]. Besides, PFC is also useful in design controller. Figure 1 shows non-cascading of the PFC regulator structure. Average modeling was the technique used to get the dynamic models of the switching converters. Current-mode control is the technique used to employs an external voltage loop and an inner current loop. A controller non-cascading structure with PFC regulator has been designed by using the current-mode control [19].

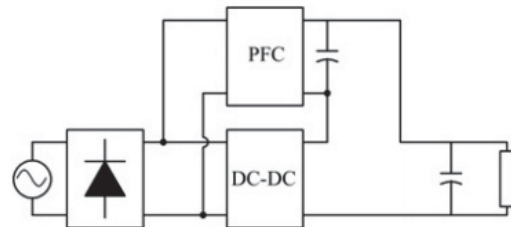


Fig. 1. PFC regulator type I-II B scheme [20]

Non-cascading structure for the PFC switching regulators has been presented by Cheung et al. [21]. In this research, the authors have been studied different category of non-cascading structures. Non-cascading structure is

better than cascading structure because non-cascading structure can reduce the power loss and prevent double processing for the input power. Several PFC switching regulator for the power flow diagram is shown in Fig. 2. This power flow diagram is helpful to classify the category of the switching regulator. The categories of the switching regulator is helping others to achieve or making improvement of overall efficiency, load voltage regulation and power factor (PF). k_1 , k_2 and k_3 is the term to represent how the power going to flow inside the switching regulator. 1 and 2 inside Fig. 2 is indicated pre-regulator and voltage regulator.

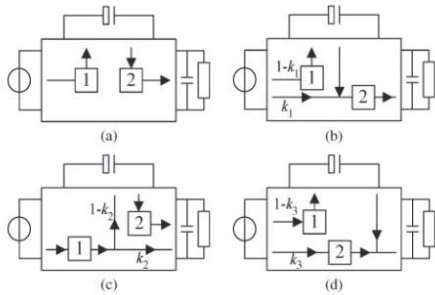


Fig. 2. Power-flow graphs for describing PFC switching regulators (a) Cascade (b) Category 1 (c) Category 2 (d) Category 3 [21]

Ji and Wang have proposed a passive filter, which can reduce the input harmonic current as shown in Fig. 3 [22]. There is a resonant tank consisting of an inductor and a capacitor just between the bridge rectifier and ac mains proposed in this research. Third harmonic input current consist of infinite impedance, which presented by this resonant tank. Therefore, ac mains remove the third harmonic current. The bridge rectifier is in parallel with the new add-on compensating capacitor. The function of this structure has several advantages, which is absorbing the distortion power, improving conversion efficiency and compensating reactive power. Unfortunately, this passive filter consist disadvantages, which are fixed, bulky and heavy compensation. The proposed method was used to eliminate the disadvantages such as distortion from AC main voltage, high value of input current harmonic, low rectifier efficiency and others. However, Ji and Wang proposed method achieve higher input power factor. This is because the input current was shaped continuous and almost nearly sinusoidal. The lower input current THD also could be maintained. In addition, a single-phase AC/DC diode rectifier with improved topology is proposed by Lee [17].

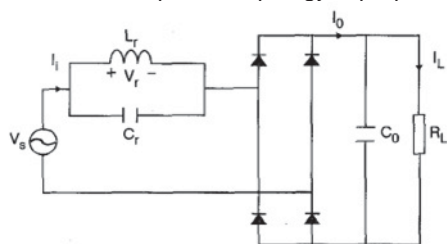


Fig. 3. A single-phase AC/DC diode rectifier topology with improved performance [23]

Active filter also used to reduce the harmonic currents. In order to maintain pure sinusoidal voltage from ac main, a voltage waveform can be subtracted or added. Nonlinear loads generate voltage distortion can be compensated by active series filter. However, industry does not use it due to high load current. Therefore, active shunt filter has been used in industry. Nonlinear load current harmonics need to be eliminated when fed into ac mains. This is the purpose of using active shunt filter. This is because small amount of fundamental current into the ac mains can be compensated

by active shunt filter. Active filter cannot do that [24-28]. Garcia et al. has proposed an active shunt filter for an economical solution. The load of the circuit is connected parallel with converter. By constructing this kind of the circuit, harmonic current can greatly be reduced. The proposed method placed an active shunt filter after the bridge rectifier structure. The purpose of this filter used to inject current at the rectified sinusoidal voltage. Hence, it can reduce the complexity of control circuit and number of power switches. The control for this active shunt circuit is become easier, which is shown in Fig. 4 [29].

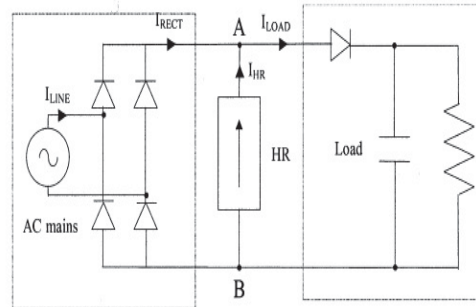


Fig. 4. Low power applications Active Shunt Filter [29]

Obviously, the control to the pre-regulator is important in PFC switching regulator. The input current can be controlled without current sensing proposed by Sivakumar et al. [30]. High input power factor can be maintained the PFC output voltage is regulated. This is due to the nonlinear control law. Sivakumar et al. propose a PFC control scheme contribute load current can be eliminated [30]. Harmonic current can become low by using average current-mode control. This can find inductor current with high accuracy. Fig. 5 shows the average-mode controller circuit for pre-regulators. The function of an integrator is to average the inductor current after a few switching cycles. High-loop-gain feedback loop used to control average current. As a result, the switching noise can be eliminated since the noise can affect current control loop. The current mode control overcome noise immunity, the error of peak to average current and others. Without the using of input voltage sensing, Rajagopalan et al. has proposed a technique to operate single-phase pre-regulators by derived the average current-mode control laws. The objective of this proposed method is to produce high power factor at input and regulate output voltage [31-32].

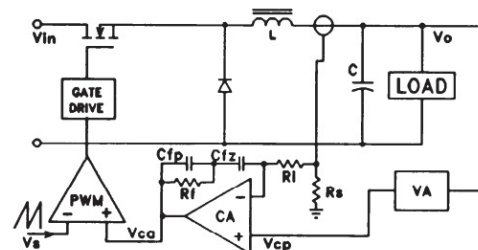


Fig. 5. Average mode controller circuitry [31]

Tse et al. introduced three-port of a PFC switching regulator which shown on Fig. 6 [33]. For this switching regulator, energy storage exists to buffer the difference between output power and the input power. The idea of this research has achieved voltage regulation and PFC. The sample of three-port model for the PFC regulator and low frequency storage is used in this method with clear out some misconception. BIFRED circuit can operate in continuous mode, which can be used as PFC regulator. For perfect regulation and unity the power factor, pc need to be buffered which given by a formula [34]:

$$(2) p_c(t) = (\hat{e})(\hat{i}_m)(\sin^2 2\pi t f_m - P_o)$$

P_o is output power, f_m is main frequency, (\hat{e}) represent the peak input voltage and (\hat{i}_m) represent peak input current. PFC is included inside the circuit for comprise the number of simple buck-boost, boost and buck converters, which are connected to the capacitive storage, output load and input voltage. This circuit produces high output voltage regulation and power factor when the presence of low frequency. The PFC switching regulator has been improved by Tse et al. by reduce the redundant power processing. The design is based on the 16 PFC regulators, which in term of power flow to make the improvement. One of the configuration dc/dc converter stages is cascading with the PFC. The rest is non-cascading structure. The PFC switching converter is more efficient based on a theoretical point [35].

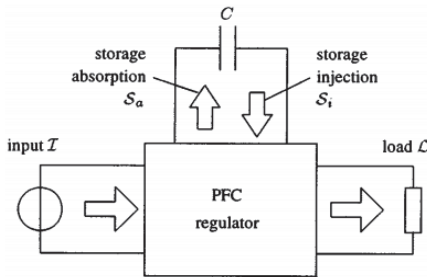


Fig. 6. Three port of the PFC switching regulator [33]

Through analysis of network, PFC regulator for a model of state-space averaged can be derived by defining the status of active switches, which are show as bellows [19]:

$$(3) \quad \frac{di_{L1}}{dt} = \frac{V_s}{L_1} - \frac{v_{c1}}{L_1}(1 - d_1)$$

$$(4) \quad \frac{di_{L2}}{dt} = \frac{V_s}{L_2} d_2 - \frac{(v_{c1} - v_{c2})}{L_2}(1 - d_1)$$

$$(5) \quad \frac{dv_{c1}}{dt} = \frac{i_{L1}}{C_1}(1 - d_1) - \frac{i_{L2}}{C_1}(1 - d_2)$$

$$(6) \quad \frac{dv_{c2}}{dt} = \frac{i_{L2}}{C_2}(1 - d_2) - \frac{v_{c2}}{RC_2}$$

where d_2 is duty ratio for the regulated of output voltage and d_1 is the duty ratio for PFC stage.

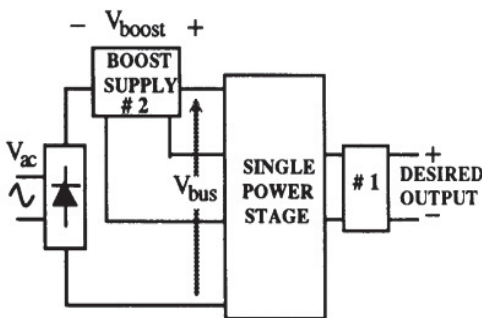


Fig. 7. Block diagram of Kheraluwala's non-cascading switching regulator [36]

Many researchers and engineers tried hard to improve the switching regulator no matter in term of input or output voltage, power, efficiency and the level of the harmonic current. Kheraluwala et al. has introduced his idea about non-cascading switching regulator [36]. The idea about the non-cascading method is shown in Fig. 7 and Fig. 8. In this method, improved efficiency of the non-cascading switching regulator is presented as only a small portion of input power processed by resonant boosting supply. The voltage regulation and PFC can be maintained because the output voltage and input current can control independently. In this process, the zero voltage switching has implemented. This

zero voltage switching allows the circuit to be designed at high frequency. By doing this, the performance will become better and reduce the cost and the size. After six years, Qian et al. have done the same thing as Kheraluwala et al. did. The only difference is Qian et al. used charge pump circuit for the PFC which Kheraluwala et al. used resonant boosting supply. Qian et al. contributed in reducing the voltage stress. The converter that is used is high efficiency and no current and voltage stress [37].

After one year, Garcio et al. has proposed the non-cascading switching regulators, which the circuit can provide tight voltage regulation and high power factor. Therefore, the efficiency of the power conversion and reduced the harmonic input current is improved in this design [38]. In 1998, a new kind of switching regulator, which is unity-switching regulator, has been introduced. The author builds the unity power factor non-cascading switching regulator by using series switching regulator. As a result, the overall efficiency has been improved by the author. The efficiency is related to the total power [39-40]. In 2004, Mishra et al. propose a method to control unity power factor non-cascading switching regulator by using a single power switch. The idea of Mishra et al. is better in term of efficiency than the conventional single stage converter topologies and improves the switch's utilization. In 2002 and 2005, Qiu, Lee and Do have introduce parallel scheme which it can produce non-cascading switching regulator. In this circuit, the authors manage to improve the power factor and reduce the current stress on the power components. Maximum voltage has been limited when voltage pass the intermediate bus capacitors. Speed has been improved by Lee in his design and idea. There is one example of the parallel scheme for the non-cascading switching regulator has been shown in Fig.8, which is Do's design. In this design, the author managed to reduce the conduction loss inside the power switch and the circuit efficiency, which reach the maximum value 91.1% [41-42].

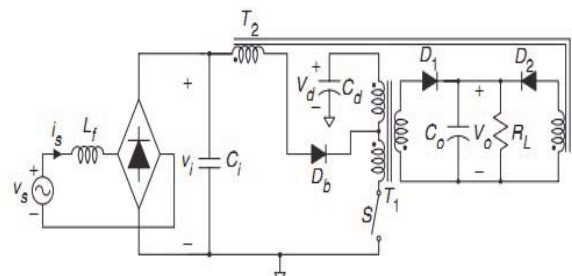


Fig. 8. Do's non-cascading switching regulator [24]

After all, non-cascading switching voltage regulator, which include pre-regulator, and voltage regulator solved the efficiency problem. Well, Tse et al. has achieved higher overall efficiency when tight output regulation exists [25].

PFC switching regulator can be grouped into three groups, which is cascade, category one, two and three. Category 1 is swap between the input-current harmonic distortion and the efficiency. Category 2 is swap between size of the storage component and the efficiency for load voltage regulation. The third category allows the swap for all the performance [22]. Fig.2(a) is a cascade structure for the PFC switching regulator. Through pre-regulator, the input power transfer from input power source to storage element. Then, the power will go to a load by passing through voltage regulator. Voltage regulator and pre-regulator fully control the output and input power. This cascade structure achieves load voltage regulation and PFC. The efficiency of cascade structure is:

$$(7) \quad \eta_{classical} = \eta_1 \eta_2$$

where, η_2 and η_1 are the efficiency of the voltage regulator and pre-regulator [20].

There are a few people propose category one non-cascading switching regulator. In 1999, Chow reviews the classic structure and proposed category 1 non-cascading PFC switching regulator. In category 1, only voltage regulator control output power. The overall efficiency is shows as below.

$$(8) \quad \eta_{category1} = \eta_1 \eta_2 + \eta_2 k_1 (1 - \eta_1)$$

where, k_1 is the ratio of the input power, which split between voltage regulator and pre-regulator [43]. The overall efficiency of category is better than classic structure. Pre-regulator is less affecting the overall efficiency because less output power processed by pre-regulator. k_1 playing an important role in category one to improve the overall efficiency and limit the input of the current harmonic distortion [22, 26].

Luo method is in the category 2. The input power will go to pre-regulator. Pre-regulator can shape the input current independently. The efficiency of the category 2 is

$$(9) \quad \eta_{category2} = \eta_1 \eta_2 + \eta_1 k_2 (1 - \eta_2)$$

where k_2 is the ratio of the output power for the pre-regulator where the power split between load and storage. The remaining power will go to storage before voltage regulator. Garcia design is the best example to show the type of the category 2 of PFC switching regulator. This is because the circuit is clearly separated voltage regulator and pre-regulator. Further increase the value of k_2 will improve the overall efficiency [21].

Kim and Garcio proposed method is under category 3. The efficiency for this category three is:

$$(10) \quad \eta_{category3} = k_3 \eta_2 + \eta_1 (1 - k_3)$$

where k_3 is the ratio of input power split between the pre-regulator and voltage regulator. k_3 also implement how much power will processed by voltage regulator. This is clear about load voltage regulation and power factor are independently control [41-42].

Discussion

In order to reduce harmonic current inside the power systems, PFC circuit is needed in power supply system. Two ways to reduce the harmonic current are input current control technique and filtering technique. These two methods can achieve PFC in any power system. The input current control technique can be achieved by a suitable control circuit together with a dc-dc converter. However, filtering technique can be divided into two, which is active and passive filter. Passive filtering technique is easy to implement by placing an inductor in series with the output. However, this method can provide only 0.75 pF in the resistive loading condition. So, the passive circuit is replaced by a resonant tank, which consist an inductor and a capacitor just between the bridge rectifier and ac main. By doing this, the conversion efficiency has been improved and the distortion of the power has been absorbed. However, the passive filters have some disadvantages like fix, bulky and heavy compensation. Due to these disadvantages, people are trying to find another way to improve the harmonic current.

Therefore, the active filtering technique has been introduced to replace the passive filtering. Active filtering technique has become a common technique to eliminate the harmonic current. Power electronic circuit use active

filter. There are several active filter has been developed or modified from active filter such as active combination of series and shunt filter, active shunt filter and active series filter. Active series filter can provide voltage waveform to maintain ac mains as active series filter can only handle the load current. Therefore, active shunt filter is popular in industry because most of the industries are using it. The purpose of using active shunt filter is to eliminate the harmonic current. Current balancing and reactive power compensation in three-phase system has been contributed by the active shunt filter. By comparing the active series filter and active shunt filter, it can be easily figured out that active shunt filter only handle the power, which is smaller than active series filter. Moreover, active shunt filter compensates less fundamental current. Thus, the combination of series and shunt filter, which can improve the current distortion and voltage in the ac mains. No matter how good the combination of both filter, it still have the disadvantages, which are higher cost and complexity of the circuit. An economical solution has been proposed to overcome the problem. The shunt filter is place after the bridge of rectifier. The function of this filter is to reduce the complexity of the circuit and power switches, as it is more complex in the point of circuitry, design and manufacturing cost.

In addition, input current controlling method is another kind of technique to reduce the harmonic current instead of active and passive filtering technique. Input current controlling technique used high switching frequency converter to shape the average input current to a sinusoidal input current with a little bit of harmonic content. The converter do not allow tight regulate dc voltage because the energy is not balanced between the dc output power and ac input power. The most common of this system is to construct the pre-regulator and voltage regulator. Pre-regulator and the voltage regulator can operate independently and the structure can obtain faster output voltage regulation. The advantage of this structure is flexible to any kind of particular specification. Energy storage element is very important and necessary tool inside any PFC switching regulator since energy storage element can provide the energy balance between the voltage regulator and pre-regulator. Energy storage element can absorb energy in the one-quarter of the ac mains period. Then, it can release the same amount of energy, which absorbed earlier in next quarter cycle. The contained energy stored inside the storage element to hold a constant energy, which is a kind of power balance condition between the output power and input power of the pre-regulator. This kind of the steady energy can maintain a stable current or constant voltage in an inductive energy storage or capacitive energy storage.

The existence of voltage regulator and pre-regulator together an energy storage element can achieve voltage regulation and pre-regulator. Previously, the input power is process serially. This brings down the efficiency of the performance. In order to improve the overall efficiency, many researchers are trying to overcome and improve the efficiency by arranging the structure. As a result, non-cascading switching regulator is invented by arranging the structure of the switching regulator in several ways. There are a few examples for the non-cascading structure. Kheraluwala et al. proposed the non-cascading switching regulator, which is built from a buck-type supply and resonant boost supply. Kheraluwala et al. has improved the overall efficiency through the using of buck type supply. Pulse Width Modulation (PWM) controlled the resonant boosting supply, where a small portion of the input power is processed by the buck type supply. The voltage regulation

and PFC can be maintained because the output voltage and input current were controlled independently. The same design proposed by Qian et al. by replacing the resonant boosting supply with charge pump circuit, which is located at PFC.

Tight voltage regulation and imperfect PFC can be provided by the non-cascading switching regulator. The circuit contains two converter, which is main converter and auxiliary converter. A use of the merged isolated converter is to divide the input power into two parts and the other one of divided power is in load. Only one converter stage is processed the directed power. The efficiency of the non-cascading switching regulator has been improved. Efficiency of the power conversion and less harmonic input current can be achieved, which is illustrated by Garcia et al.

The power flow arrangement is important in the PFC switching regulator. This power flow is located between the voltage regulator and pre-regulator. Unity PF can be achieved by a portion of the power, which gets the load and the other reach the load by passing through the voltage regulator after splitting the pre-regulator. Subsequently, less rectifier of non-cascading switching regulator has been proposed. Voltage regulator, which is represented by a series-switching regulator used to build unity PF non-cascading switching regulator. This series-switching regulator used to compensate difference between output voltage from the pre-regulator and output voltage from the non-cascading switching regulator. The overall efficiency is more than 97% in full load condition. Mishra et al. proposed the method by using single power switch to control the unity PF non-cascading switching regulator. A merged isolated converter and flyback converter used to build the non-cascading switching regulator. Both converters can operate in Direct Current Module (DCM) for the PFC. Power from the ac mains is transferred to the load by the flyback converter. By depending on the transformer turns ratio, output voltage and rectified input voltage level, merged isolated converter manage to operate in the forward or flyback mode.

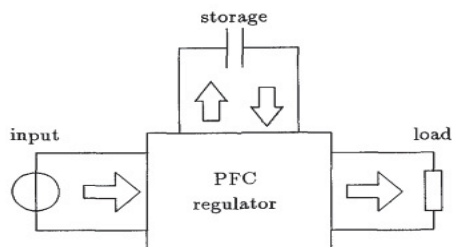


Fig.9. Three port of the switching regulator [43]

In between 2002 to 2005, parallel PFC scheme also can implement out the non-cascading switching regulator. Qiu, Lee and Do construct the non-cascading switching regulator by making the voltage regulator and pre-regulator in parallel connected to each other. The output load also connected in parallel with the voltage regulator and pre-regulator. The voltage regulator and pre-regulator draw the input power source simultaneously. Based on these propose method, the input power is split into two paths. One of the powers is controlled by the pre-regulator before it reaches to output load. Meanwhile, another one is processed by the voltage regulator before the power reaches the load. As mention earlier, non-cascading connection between the voltage regulation and pre-regulator can overcome the efficiency problem, which is faced by switching regulator. In order to improve the efficiency, the partial power-processing concept is very important. By fulfilling harmonic current emission standard and tight voltage regulation, the overall efficiency is increased for a switching regulator. Tse et al. has

contributed the idea of synthesis minimal practical non-cascading switching regulators. Based on Fig. 9, the three-port network terminates in an output load, energy storage element and input voltage. The load and input port allow the energy to transfer in one direction. Meanwhile, the bidirectional energy flow is allowed by an energy storage element. The energy flow for all the port was show by the arrow as shown in Fig. 9.

Two converters needed to build the switching regulator if the power output and input port is connected. The power converts from input port to energy storage and load to ensure the switching regulator to contribute what is necessary for the power buffering function. After that, converter must not allow the power flow from a port back to itself to make sure the minimum number of the power flow paths. Based on the rules, the ports are connected by three power flow graphs, which are shown in Fig. 10.

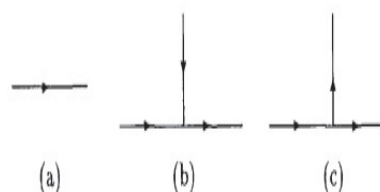


Fig. 10. Power flow graph for a) Type I b) Type II and c) Type III [43]

The power flows among the three ports is fully describe in the power flow diagrams. There are four structure of the power flow, which is show in Fig. 2. The labels 1 and 2 inside the Fig. 2 are two converters [36]. The clearer picture of the evolution in terms of method and the PFC switching regulator to reduce the harmonic current is shown in Fig. 11.

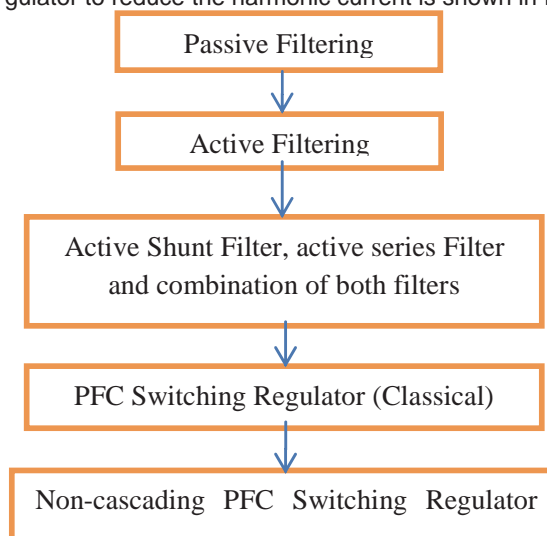


Fig. 11. The evolution for reducing the harmonic current and switching regulator

In order to build an efficient switching regulator, non-cascading structure is the best way to implement it. This kind of the structure can be achieved PFC and tight output regulation. There are several types of the non-cascading PFC switching regulator. Choosing an appropriate type of the non-cascading switching regulator is also important. Efficiency, load voltage regulation and input current harmonic are the performance of a switching regulator. Those terms need to be considered all the time. There are three types of the non-cascading switching regulator, which are category 1, category 2 and category 3. Category 1 offers and allows the tradeoff between the input current harmonic distortion and the efficiency. Category 2 allows

and offers the tradeoff between the size of storage element and the efficiency for load voltage regulation. On the other hand, category 3 switching regulator allows the tradeoff for all the performances. Many research have been done to evaluate these three categories if the switching regulators to test the simulation results.

Based on Fig. 2, different types of switching regulator have been described by using power flow diagram. The diagram shows how exactly the power transfer from one port to another port. The arrow inside the Figure shows the direction of power flow. Like mentioned earlier, square box 1 is the pre-regulator and box 2 is a voltage regulator. Energy storage permits bidirectional power flow. Voltage regulator only permits the power flow in one direction. Fig. 2 (a) is a cascade structure. Through pre-regulator, total input power transfer to storage element from input power source. Then, the power transfers to a load by going through voltage regulator. This cascade structure has achieved the load voltage regulation and PFC. Because of serial power process, the efficiency for this cascade structure has been degraded

Category 1 switching regulator is shown in Fig. 2(b) where, voltage regulator is fully control the output power. Therefore, the control for this load voltage is fully independent. The input power is divided into two. One part of the power is flow to voltage regulator and the other one is flow to pre-regulator. Then, both of the power is flow to a load. Table 1 represents the comparison performance for the classical and three different categories of switching regulator.

Table 1. The comparison performance for the classical and three category switching regulator

	Power Factor	Load voltage regulation	Overall Efficiency
Classical	Perfect	Independent	Low
Category 1	Dependent on k_1	Independent	Dependent on k_1 and dominant in η_2
Category 2	Perfect	Rely on energy storage	Dependent on k_2 and dominant in η_1
Category 3	Dependent on k_3	Rely on energy storage	Dependent on k_3 , η_1 and η_2

From Table 1 it is found that, k_1 is the ratio of the input power, which split between voltage regulator and pre-regulator. k_1 represents the one part of the power, which is flow to voltage regulator and the other one is flow to pre-regulator. Clearly, the tradeoff is possible between the PF and the improvement of the efficiency for this category-switching regulator.

The power flow for category 2 has been show in Fig. 2 (b). The input power is connected to pre-regulator, where pre-regulator can shape the input current independently. k_2 is the ratio of the output power for the pre-regulator, where the power split between load and storage. The output power from the pre-regulator is represented by the k_2 , which flow to the load. Whereas, the remaining of the output power flows to the storage then reach voltage regulator. Obviously, the load regulation and the size of the energy storage for this category-switching regulator can have improvement for the efficiency.

The power flow for the category 3 switching regulator shows in Fig. 2 (c), where k_3 is the ratio of input power split between the pre-regulator and voltage regulator. k_3 also implement how much power is processed by voltage regulator. Obviously, the load voltage regulation and the PF

cannot control. This k_3 indicates tradeoff between PF, load voltage regulation and efficiency. This category 3 of the switching regulator gives flexibility to obtain a better performance. Table 1 shows the comparison performance for classical and three category of the switching regulator.

By comparing the power factor, load voltage regulation and overall efficiency to obtain which category is the better switching regulator. To achieve perfect power factor, classical switching regulator and category 2 is utilized. This is because pre-regulator inside the classical switching regulator and category 2 switching regulator can completely control the input current. Only small amount of the input current controlled by the pre-regulator for category one switching regulator and category 3 switching regulator. Both of the categories split factor has deteriorate the power factor.

Load voltage regulation cannot be regulated fully by category 2 switching regulator and category 3 switching regulator's voltage regulators. As these categories need to depend on the energy storage. Whereas the classical switching regulator and category 1 switching regulator do not depends on the energy storage.

By comparing classical switching regulator, category 1 switching regulator, category 2 switching regulator and category 3 switching regulator in term of overall efficiency, Table 1 shows that category 3 obtain the highest overall efficiency. As the voltage, regulator and pre-regulator are connected parallel to each other. This kind of the structure can avoid the voltage regulator and pre-regulator process the input power serially. k_1 in category 1 switching regulator govern the overall efficiency and the efficiency of the voltage regulator. Whereas the k_2 in category 2 switching regulator dominate the overall efficiency and the efficiency of the pre-regulator.

Conclusion

Input current controlling and filtering are the techniques, which used to reduce the harmonic current emission. Input current control technique can operate the power levels, which is below the several kilowatts. In order to satisfy the fast voltage regulation and low input harmonic current distortion, voltage regulator and pre-regulator must exist to form a switching regulator. The voltage regulator and pre-regulator can form a chain connection to implement a switching regulator and it can process the input power. The switching regulator's efficiency has confirmed deteriorate. Non-cascading switching regulator is believe to improve the power redundantly and the efficiency.

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