1. INTRODUCTION

1.1 OVERVIEW

There has been a growing interest in current harmonics with an increase in the use of static power converters. These converters produce current and voltage distorted waveforms. The result is harmonic pollution that degrades the power quality [A1], [A2], and [A3]. Such harmonic distortion leads to losses in transformer cores and motors [A4]. In addition, they can cause more serious problems of interference with control systems and computer networks between subsystems. Furthermore, they may cause poor power factors and eventually lead to increases in utility costs. To provide for safe operations and to meet harmonic standards such as IEEE 519 [A1], it is necessary to eliminate harmonic distortions from the system by introducing negative harmonics into the power network [B1] and [B2].

Until now, various active filter topologies have been developed to solve harmonic problems. There is a wealth of literature on its characteristics and controls [B3] - [B24]. However, its applications are limited to high-voltage active power filter applications that require fast dynamics corresponding to load variations. For high-voltage applications like maglev systems, some problems have been encountered while dealing with the practical control and implementation of main topologies. These include:

- Voltage unbalance between split dc capacitors;
- Indirect clamping of inner switching devices; and
- Series connected clamping diodes.
To overcome these problems, a multilevel structure with flying capacitors was proposed in recent years [D8]. This approach obviously overcomes the limitation of diode-clamped multilevel converters. The flying capacitor multilevel converter (FCMC) has not been widely applied in industry. Nevertheless it seems that it has important advantages over the diode clamp multilevel converter (DCMC) [D1] - [D7]. This is because it uses a clamping capacitor across a two-switch pair. Although the diode technology is remarkable, high stresses still remain when the diodes turn off. On the other hand, to avoid the recovery problem associated with the diode [C25], the switching modulation that keeps voltage balance between each leg is limited to the DCMC [D10]. However, the FCMC has a wealth of redundant switching states that balance the dc-link capacitors, [D9], [D11], [D32], and [E17].

In spite of this, there is a fundamental problem dealing with voltage balancing between flying capacitors and each leg under practical operation, [E10] and [E11]. The major problem is due to unequal parameters of the converter caused by different main device tolerances and unbalanced packaging. This leads to voltage unbalance and thus, unsafe operation. For its balancing, even the FCMC theoretically requires the symmetric switching of control signals with a phase shift. Voltage unbalance of the flying capacitor in practical applications may be observed due to unequal parameters [D33].

Up to now, there has been very little work done to solve a fundamental problem in the FCMC applications [D8], [D23], [D30], [E3], and [E10]. Since most of the research was focused on uni-directional dc-dc converter applications, this problem was not considered to be a major concern. Through simulation and experimentation, it was discovered that this topology is not available for bi-directional applications without adding a passive voltage balancing circuit or voltage control loops. For voltage balancing between flying capacitors, various approaches can be considered using voltage stabilizers and switching modulations. First, controlling each capacitor voltage within a few cycles makes it possible to maintain a voltage balance. Secondly, the capacitor voltage can be controlled by a modulation scheme, which introduces small changes in the switching instants. In this case, the suggested approach changes slight distortions to the voltage but allows selective charging of each capacitor without requiring an increase in the number of switching events.

1. INTRODUCTION
1.2 STATE OF THE ART

This section describes the state of the art soft-switching multilevel active power filter technologies. These technologies incorporate diverse areas in literature, including power quality and harmonic filters, multilevel active power filters and its soft-switching topologies, and various control methods.

1.2.1 Power Quality and Active Filters

It is well known that power quality is an essential in a power system. Recently, the use of static power converters makes it a growing interest due to the current harmonics that degrade power quality [A5], [A7], [A9], and [A12]. This is because these converters use current for part of a cycle through multiple paths in order to converter alternating current to direct current, and vice versa. It causes harmonics with non-sinusoidal current waveforms, which contain multiples of the fundamental frequency of the utility. Moreover, they may cause poor power factors for a perfect sinusoidal utility and eventually lead to increases in utility costs.

In order to overcome these problems, various approaches have been proposed [A6], [A8], [A10], and [A11]. In general, harmonic filters are widely used to solve the problems associated with harmonics. This is because the filters can significantly reduce harmonics and improve power factors, simultaneously. They have essentially two different types of structures, the passive power filter (PF) and active power filter (AF).

The passive filters consist of passive components, for example, capacitors, inductors, and damping resistors. Such filters may become the limitation for harmonic compensation with its combinations, while the system impedance varies corresponding to load variations. This could lead to an unacceptable compensation problem with the inflexibility of the filter. However, in many cases, passive filters offer a simple and effective way to mitigate harmonics, if the harmonics are located inside a narrow frequency range specifically, if the impedance of the
harmonic source is high, and the network does not present resonance close to harmonic frequencies. In general, the passive filters are limited in the following aspects [A9] and [A12].

- Adaptability on power network impedance and frequency variations,
- Versatility to detune different component characteristics, and
- Flexibility to avoid resonances with the network.

On the other hand, with significant development of power converter technology, active filters are widely used in industry, [B1] and [B2]. As active filters consist of active power electronic components, they use a controllable source to adjust a desired voltage or current waveform in the network. It can also quickly compensate for the harmonic current variations by using fast switching devices. Thus, active filters have the advantage of compensating ability for harmonics without fundamental frequency reactive power concerns. This means that the size of the filter can be less than that of the comparable passive filter for the same nonlinear load. Therefore, the active filter can control the system resonances by changing the harmonic related frequency. The characteristics of active power filters are as follows:

- Covers a wide frequency range,
- Achieves a fast dynamic response with high-frequency active switching device,
- Provides load-adaptive compensation for widely nonlinear load variations,
- Controls network resonances, and
- Reduces size and volume using minimum passive components.

For this purpose, a number of different topologies of active filters are being proposed and utilized on various power electronics systems [B3] - [B11]. These topologies need their required component ratings and control methods for the loads to be compensated [B25]-[B51]. For high-voltage applications, hybrid power filters that combine with an active filter and a passive filter have been proposed to overcome limitations of the fundamental voltage of active switches across an active filter by using a fraction of the line voltage [B38] and [D25]. Thus, they reduce the apparent power cost in specific applications.
On the other hand, along with the growth of interest in harmonics caused by the increased use of static power converters, the utility companies in recent years are forcing customers to meet harmonic standards such as IEEE 519 [A1], IEC 1000-3-2 and IEC 1000-3-4 [A2], [A8], and [A11]. Among them, the IEEE 519 standard provides strict limitation on harmonic distortions according to two distinct criteria, namely, (1) there is a limitation on the amount of harmonic current that a consumer can inject into a utility network, and (2) a limitation is placed on the level of harmonic voltage that a utility can supply to a consumer. This standard clarifies the responsibility of the customer for limiting harmonic currents injected onto the power system [A4].

The standard IEC 1000-3-2 describes the basic emission limits of disturbances caused by equipment connected to public low-voltage supply systems: Part 2 is for $\leq 16$ amps and Part 5 is for $\geq 16$ amps. In addition, the IEC 1000-3-4 standard recommends harmonic limitation for three-phase systems.

In conjunction with deregulation, different utilities may have different requirements for the level of harmonic control that customers have to meet. This means that the utility is responsible for maintaining the quality of the voltage waveform. Recently, the customer-utility point of common coupling (PCC) between the utility and customer is determined to prevent degradation of power quality on the utility grid, [A7] and [B51]. Under this situation, harmonics has been one of the major issues debated by standards committees. This is due to the difficulty of defining and identifying a regulation range of harmonics. Additional analysis is required in order to adequately define harmonics for use in these standards. This is increasingly a priority for people responsible for power quality and the end user as well.

### 1.2.2 Multilevel Active Power Filters

Currently, the research trends in the field of power electronics, are focusing on improved power quality. For a high-voltage utility, a multilevel active power filter is a logical selection without extending its device ratings. This is because a multilevel converter can synthesize the output voltage waveforms with stepping levels. It provides less switching stress on its devices
and a better harmonic spectrum compared to that of conventional two-level converters. Furthermore, by increasing the number of voltage levels, the output voltage waveform of the converter is reduced due to fewer harmonic distortions [D12].

Various multilevel converters have been used in utilities and energy applications [D13], [D22] and [D25], harmonic compensators [D12], [D17] and [D23], and motor drives [D14] - [D16], [D18] - [D21], and [D24]. Historically, the basic concept of a three-level converter using switching devices is based on a neutral point clamped converter for motor drives [D1]. This converter consists of two capacitor voltages in series and uses the midpoint between the positive rail and negative rail by clamping diodes to get the staircase output waveform. This structure has been extended to a multiple of the output waveform proposed in [D2] - [D7].

However, their applications are limited to such problems as voltage unbalance between split dc capacitors, indirect clamping of the inner switching devices, series connected clamping diodes, etc. By using an auxiliary resistive clamping network, a diode clamping inverter can be implemented without the series association of the clamping diodes [D10]. It can solve the indirect clamping problem of the inner devices. The work on the multilevel converters is mostly focused on the development of new multilevel converter topologies, in conjunction with improvement of their modulation methods and control algorithms [D14] - [D16]. At the present time, use of these multilevel converters has become popular for utility and drive applications. On the other hand, significant development of power semiconductor technology can provide a hybrid multilevel structure with a high-switching and voltage blocking capability. The converter uses a hybrid approach involving integrated gate commutated thyristors (IGCT’s) and insulated gate bipolar transistors (IGBT’s). It is typically suitable for high-performance, high-power applications. However, an accurate switching modulation is required for each device, which has quite different switching characteristics.

An alternative choice is a multilevel converter with cascaded H-bridge configuration [D12] and [E18]. Since this converter consists of a full-bridge single-phase inverter, it can easily be extended to increase the number of levels without introducing complexity in topology. However, the switching modulation needs to be optimized for high performance applications, due to a limited combination of switching patterns.
To overcome these problems, an innovative multilevel structure replacing clamped-diodes with flying capacitors was proposed in recent years, [D8] and [D9]. This converter obviously overcomes the limitation of diode-clamped three-level converters and offers new interesting properties. Basically, multilevel converters are available for active power filters, which can be used for harmonic compensations [B7]. They are connected in series and/or parallel connection between the utility and nonlinear loads. By inserting negative harmonics into the network, it can eliminate harmonics from the system. Although they have quite different structures and operation, depending upon their voltage clamping methods, there is a wealth of literature on their characteristics and controls, [E10] and [E11].

The flying capacitor multilevel converter (FCMC) is relatively new and has not been widely applied in industry. Nevertheless it seems that it has the most important advantage over the diode clamp multilevel converter (DCMC). This is because it uses the minimum number of clamping diodes, by placing a flying capacitor across a two-switch pair. Although the diode technology is remarkable, high stresses still exist while the diodes turn off. To avoid the recovery problem associated with the diode, the switching modulation is limited to provide for the voltage unbalance between each leg. Since the FCMC has a wealth of redundant switching states that allow dc-link capacitors to be balanced, there are enough combinations between switching states to provide for voltage balancing [D12], [D23], [33], and [E17].

Furthermore, compared to the diode clamp multilevel converters, the FCMCs eliminate two extra clamping diodes and a mid-capacitor point for each switch pair. As a result, the FCMC structure is simplified, and the reverse recovery problem of the clamping diode is eliminated. The drawback of this topology is that the control of the converter is more complicated and needs a large number of capacitor. Fortunately, the size of flying capacitors can be reduced by an increased switching frequency.

1.2.3 Soft-switching Techniques

Recently, soft-switching inverter/converter (SSC) technologies have been developed and have become an attractive and desirable option in industry [C1], [10], [C15], [C18], and [C30].
These technologies are scoring well over the traditional hard switching converter (HSC) technologies. Since the conceptual SSCs do not create over-voltage or over-current spikes in the main device and auxiliary switching devices, it has enabled the benefit of achieving higher efficiency and reliability, lower EMI, lower cost, and smaller heat sinks compared to the traditional HSCs, [C2] and [C3].

There are two major categories of soft-switching techniques: zero-current transition (ZCT) and zero-voltage transition (ZVT). First, the ZCT technique uses the inductor and capacitor (LC) resonant tank circuit in series with the auxiliary switch and clamping diode. It can reduce the turn-off switching losses in the soft-switching circuit while forcing a zero current on the switch. On the other hand, the ZVT technique uses a resonant branch with a snubber capacitor. The resonant branch places the resonant circuitry in parallel with the main switches. With these techniques, various soft-switching topologies have been proposed and developed in industry.

A ZCT topology was first introduced in [C8]. The circuit operates with the main switch turning off at zero current, and thus, use of the ZCT circuit can dramatically reduce the turn-off switching losses. However, the drawback of the circuit is in the turn-on switching losses. The soft-switching circuit does not reduce the turn-on loss. Thus, the diode reverse recovery of the device, in the case of the IGBT devices, causes more turn-on switching losses. In addition, since the current rating of the main device is determined by adding the load current, this topology requires a high peak current rating on the main device. Moreover, the auxiliary switch after resonance, turns off under a hard-switching condition, which results in a limitation for high voltage applications. Nevertheless, this topology has an attractive feature for high-frequency-low power converter applications due to easy implementation and fixed resonant frequency operation.

On the other hand, a modified design (with a different arrangement of the auxiliary switch and clamping diode), has been proposed in [C10]. With both turn-on and turn-off signals on the soft-switching circuit, the total switching losses can be significantly reduced, even when limited to the current peak on the main switch. When both turn-on and –off switching is required, it generates more circulating energy in the resonant circuit than that of the single side resonant mode. Thus, this topology needs twice the voltage rating for the resonant capacitor to the dc
In order to reduce voltage and current stresses on the auxiliary circuit components, an improved ZCT topology was recently proposed [C27]. The topology has major fundamental limitations: (1) precise switching timing sequence is required, and (2) a minimum pulse width is limited due to both sides switching between turn-on and turn-off.

An alternative technique is the ZVT topology. Various ZVT topologies have been proposed in the recent years, including an auxiliary resonant commutated pole (ARCP) cell [C4], [C6], [C11], [C13], [C14] and [C17], an active snubber, [C16], a coupled inductor based ZVT cell [C5], [C7], [C12], [C28] and [C29], and an auxiliary resonant snubber inverter (ARSI) cell [C9], [C18]-[C26] and [C30].

An auxiliary resonant commutated pole (ARCP) cell was introduced in [C4]. The auxiliary commutation circuit consists of one bi-directional switch and one resonant inductor for each pole. The resonant inductor is placed in parallel with the leg pole. Since the ARCP topology generally is required on the boost current to divert the load current direction, it enables the main devices to turn-on at zero current and turn-off by the added snubber capacitors. Thus, it can be effectively used for high voltage applications. The main features of this topology is that the auxiliary switches block only half the dc-source voltage by the use of two split capacitor sources and are turned off at a zero current condition.

The use of coupled-inductor based ZVT converters has attractive features for high-power applications. The coupled inductor helps prevent half of the resonant current in the auxiliary circuitry from flowing through the auxiliary soft-switching circuitry [C7]. The main feature of this topology is a minimum voltage and current rating of the auxiliary switch. The drawback of this topology is the design of the coupled-inductor because it is more complex than the transformer itself. Nevertheless, this topology is simple and effective at achieving ZVT for the main switch devices.

Finally, an auxiliary resonant snubber based ZVT converter consists of only one auxiliary branch circuit added across the load as compared to a conventional converter. The converter, similar to the inverter used in [C9] and [C18] eliminates the reset current by using the load side resonant tank and employs adaptive control of the resonant current corresponding to load current.
variations. However, the soft-switching converter is limited by its inability to be applied to a multilevel inverter, due to control feasibility.

In addition, a new soft-switching multilevel inverter topology for active power filter applications can be achieved for switching improvements during high switching frequency operations. The usage of soft-switching multilevel inverters has several benefits. Not only does it utilize maximum switching operations without additional switching losses, it dramatically reduces high voltage and current stresses by comparing it to that of a hard-switching inverter. Thus, it can reduce switching losses, reduce voltage/current stress, reduce EMI, and allow a higher switching frequency of the converter and inverter applications. However, there are no technical papers found to support active power filter applications.

For many applications, various zero-voltage switching (ZVS) schemes for three-level capacitor clamping converters can be implemented based on the dc link LC tank [D26], auxiliary resonant-commutated pole (ARCP) [D27] and [D28], assisted-transformers [D29] and [D30], and coupled-inductors [D31] and [D33]. The main switches of all converter topologies work with ZVS through auxiliary resonant circuitry, without imposing any voltage/current spikes on the main devices or any extra control complexities. Consequently, a three-level flying capacitor inverter system can operate at a promoted switching frequency and becomes more eligible to be considered for high-voltage advanced active filter areas.

In addition, a zero voltage soft-switching scheme with an autotransformer can completely eliminate the resetting problem associated with the coupled-inductor. In addition, the inverter with the assisted transformer can solve a reset problem [D29]. However, it cannot reduce the current rating of auxiliary switches.

1.2.4 Control Issues of Active Filters

A control algorithm is required to get fast response of active power filters corresponding to load variations. For this, the controller should have a powerful signal processor that is able to support a quite sophisticated calculation process, including complicated frequency
characteristics. To extract the harmonic component of the active filter current, several control algorithms are available using time domain and frequency domain processing as follows:

- Use of notch filter having a very high order,
- Use of fast Fourier transform involving heavy calculation after at least a fundamental period for the acquisition of current measurements, and
- Use of calculation of the instantaneous power that circulates in the load.

Among them, it is well known that the instantaneous power control algorithm is widely used in active power filter applications [B13], and [B20]. Furthermore, as the algorithm is derived from the Park’s transformation that is based on two-axis components, the calculation process is very simple and thus, it can quickly compensate for harmonics corresponding to nonlinear load variations.

The principle of the algorithm is that the main source voltages and load current are first transformed into two-axis representations. Based on this representation system, the instantaneous real power and imaginary power are calculated. Since the calculated powers are based on the two-axis system, it is necessary to transfer to those of a three-phase system. After that, the reference signals for the compensation current can be obtained. These reference signals and detected output currents of the active filter can be sent to a current controller to generate the pulse-width-modulation (PWM) signals required for the operation of control signals. To date, various control methods have been proposed.

1.2.5 Fundamental Issues of Flying Capacitors

Even though the flying capacitor based multilevel converter was discovered in the 1990’s [D8], its topology was not given much attention until the mid 90’s. After the modeling and characterizing by [D9], its use has been widely used in dc-dc converter applications. In spite, this topology is limited to bi-directional applications that require a voltage balance between each leg and /or flying capacitors. The fundamental problem associated with unequal parameters for bi-
directional applications needs to be addressed. Of course, to achieve the voltage balance between clamping capacitors, the following aspects are considered [B49], [D30], and [D33].

(i) Voltage synthesizing: It is very important to select optimum switching states for multilevel inverter applications because the switching action of each switching cell is dependent upon the other cell under fundamental frequency modulation.

(ii) Phase-shifting: The topology responds to a set of gating signals with phase shifting by $2\pi / p$, where $p$ is the number of multilevel cells. This shifting will produce an output voltage waveform that has minimum harmonics up to $p$ times the switching frequency.

(iii) Instantaneous current stress on flying capacitors: Since the current stress is related to the duty cycle and load power factor, the maximum current stress occurs when only reactive power is processed.

(iv) Voltage sharing between flying capacitors: The balanced voltage sharing during dynamics will guarantee successful operation. Unequal voltage sharing causes output distortion, and thus will subject the switches to destructive voltage stress.

Therefore, it is necessary to investigate the relationship between parameter variations in the converter. For this purpose, an accurate model is required to identify the operation of steady-state modes as well as the dynamic response of the capacitor voltages in ideal conditions.

In addition, the main circuit operation issues, with regard to the clamping voltage stability, flying capacitor stress, and output voltage spectrum are unknown under soft-switching operations. To identify these parameter sensitivities under soft-switching operations, an optimized auxiliary circuitry is required to analyze voltage stress and resonant impedance of the auxiliary circuitry.
1.3 **SCOPE**

This dissertation provides an insight into the development of the voltage balance techniques of flying capacitors used in soft-switching multilevel active power filters. The major objectives of this research are to identify the voltage balancing issues and to develop voltage stabilization techniques for flying capacitors. In general, the performance of an active power filter highly depends on the design of the inverter topology, interface inductor, energy storage capacitor, and controller which calculates compensating current references and controls the currents and dc capacitor voltages. Achieving high performance of the filter represents a challenge for increasing a fast response, reducing cost and size, improving power quality in utilities, and suitability of system operation, particularly when the filter is under industrial operation. Based on this survey the following key issues are identified as those issues to be addressed in this dissertation:

(i) The study addresses a newly developed soft-switching multilevel inverter with flying capacitors for active power compensations. The proposed inverter consists of a flying capacitor based multilevel inverter and additional soft-switching circuitry with inductor coupling. This approach is feasible for challenging active power filter applications.

(ii) Major issues are discussed that include fundamental characterization of FCMC such as flying capacitor voltage balancing, voltage synthesisization, dv/dt stress, parameter sensitivities, switching modulation, etc. This fundamental analysis provides a basis for the voltage unbalance problem created by flying capacitors. However, voltage unbalances may be observed under different component behaviors and packaging techniques in some circuit applications, in spite of the self-balancing of the capacitor voltage in a given switching cycle. An unbalanced voltage such as this, results in an unstable condition of the converter. The major
reason for the voltage unbalance are (1) different switching characteristics related to each switching device loss, (2) different capacitor conduction losses, (3) parasitic components related to the packaging, and (4) external noise disturbance. Parasitic components and external noise disturbances can be minimized by advanced packaging techniques.

(iii) With soft-switching techniques, the switching frequency of the active filter can be increased up to 10 kHz in order to reduce the size of the interface inductor and the flying capacitor. In addition, the use of high-frequency operation in the active filter makes it possible to achieve fast response for load variations. In respect to soft-switching operations, the proposed circuit topology can overcome the limitation of voltage-balancing between the dc link capacitors. Two inner devices in a multilevel inverter can then be clamped like that of the conventional two-level inverter.

(iv) To solve the fundamental problems associated with voltage balances between flying capacitors, a new voltage stabilizer is proposed. The proposed controller with proportional-integral (PI) gains is an effort to get the advantages of both good transient responses from the proportional and error elimination from the integral. For better performance, an overall control scheme with the functions of an active filter is defined based on instantaneous reactive power (IRP) control theory.


1.4 DISSERTATION OUTLINE

A significant amount of research has been devoted to this dissertation. The research ranges from fundamental voltage balancing techniques to control issues of a proposed active filter. The proposed active filter is geared towards meeting today’s industrial demand for high reliability, high efficiency, and clean power. The most important characteristic sought is viability of acceptable voltage balancing based on instantaneous reactive power theory, which is verified by both simulation and experiment. This research effort concentrates on providing analytical reasoning along with extensive simulation-based and experimental verifications of the proposed filter. This dissertation covers the design, analysis, and control of the proposed soft-switching multilevel active power filters.

Chapter 2 describes a newly developed soft-switching multilevel inverter that is proposed and discussed with its active power filter application. The operation principle and control of the proposed inverter are explained and characterized. The inverter is verified through computer simulation and experimentation with a prototype inverter.

Chapter 3 covers the fundamentals of the proposed inverter for active power filters based on the voltage balancing for flying capacitors. The major issues in the inverter are focused on voltage unbalance between flying capacitors and switches. These voltages unbalances are analyzed and characterized as: 1) flying capacitor voltage, 2) dc split capacitor voltage, 3) flying capacitor characteristics, and 4) voltage synthesizing.

Chapter 4 discusses the overall controller for the proposed active filter based on instantaneous reactive power theory. The proposed control scheme is designed for compensation of harmonics within two control loops: one is a fast loop that is used to control the output current in the active filter, and the other is a slower loop used to maintain voltage balancing between the
flying capacitor and dc bus voltage. The models for the proposed control loop are analyzed and discussed with analytical simulation.

Chapter 5 presents the simulation and experimental results of the proposed active power filter. In this section, voltage stabilization measurements and control factors are identified based on the controller, resulting favorably. Further experiments were conducted for successful operation at any condition.

Chapter 6 concludes the dissertation, summarizes the experimental results, and formulates recommendations for further study.

The Appendix’s contain peripheral topics such as the proposed soft-switching techniques and switching characteristics of the IGBTs under different soft-switching conditions.