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Introduction to Conducted Emission in Adjustable Speed Drives

It is never possible to predict a physical occurrence with unlimited precision.

Max Planck

1.1 High-Frequency Emission of Switch-Mode Power Converters

Switch-mode power conversion method is generally based on the switching regulator that allows controlling output voltage and current by changing the ratio between on-time and off-time of switches by using different modulation patterns. The efficiency of switch-mode power conversion depends mostly on switching characteristics of semiconductor switches. Reducing of transistors' switching times allows decreasing switching losses and increasing carrier frequency of modulation [1,2]. Faster switching of switches in switch-mode power converters, although very beneficial for energy conversion efficiency, unfortunately results in faster voltage and current changes [3,4].

Any rapid change of voltage or current in electric circuit, from the EMC point of view, is a source of electromagnetic emission that can be potentially harmful to other equipment. Therefore, these emissions should be limited to provide undisturbed operation of electric devices. Electromagnetic emission spectrum width, which directly depends on the rate of change of voltages and currents, in currently used power electronic devices can easily achieve megahertz band [5,6].

With the increase of frequency of electromagnetic emission, effectiveness of its unintentional propagation capabilities usually increase, thus enabling the generated disturbances to be transmitted more easily by means of conduction

High Frequency Conducted Emission in AC Motor Drives Fed by Frequency Converters: Sources and Propagation Paths, First Edition. Jaroslaw Luszcz.

or radiation phenomena. To reduce electromagnetic emission of switch-mode power converters, wide-band passive filters and shields are most often used. Design and implementation of EMI filtering components are troublesome and expensive, especially in low frequency (LF) range [7–9], below 9 kHz, where sizes of filtering components are considerable, as well as in high frequency (HF) range, above 9 kHz, where radiated and conducted emission leakages are very difficult to predict and avoid at the design stage [10,11].

Furthermore, the reduction of electromagnetic emission usually becomes more difficult with the increase of converter's rated power because of the overall size of converter's components that in turn results in increase of parasitic couplings, whose effects are more difficult to avoid or even to decrease [12–14].

1.2 Characteristic Issues of Conducted Emission in Adjustable Speed AC Motor Drives

ASDs consisting of AC motors and FC containing voltage source inverters (VSI) controlled according to pulse width modulation (PWM) patterns are exceptional in several ways in relation to many other types of switch-mode high-power converters integrated with power systems.

First, in recent years the total power of ASD used in residential, commercial, and industrial environments has been increasing significantly. This considerable increase is observed primarily in rapidly growing number of installed low-power ASDs, below few kilowatts, in critical environments containing electromagnetically sensitive equipment, for example, air-conditioning systems, intelligent and automated buildings, fully automated production lines, and energy-saving installations. On the other hand, the rated power of single ASD used in heavy industry and directly integrated with the power system at distribution level achieves quite often rated power even in megawatts. ASD of high rated power of megawatts are more often powered directly from medium voltage (MV) grids, which results in commutation of much higher DC voltages and leads to increased generation of conducted emission [15–17].

Second, currently used semiconductor switches, mostly IGBT transistors of different generations, commutate high voltages and high currents in shorter time in order to decrease switching losses and allow using higher modulation carrier frequencies. High-power IGBT transistors used in high-power frequency converters exhibit relatively large parasitic capacitances between semiconductor substrate and cooling subbase. Higher levels of switched voltages together with shorter switching times and more considerable parasitic couplings result in significant increase of transient capacitive stray currents flowing between energized and grounded components, which are essential for conducted emission generation and propagation [18,19].

Third, load of FC—AC motor windings together with motor feeding cable—cannot be precisely taken into account at the design stage of FC, because it is widely dependent on requirements of singular application. Thus, HF parameters of FC load can be known only at installation stage and can usually differ significantly in each particular application of the same type of FC [20,21]. The physical size of FC load, feeding cable with windings, is usually much longer compared to distances encountered inside FC and in many applications it can obtain the length comparable to the wavelength of transmitted harmonic components of signals. In such applications, more effective propagation of generated conducted emission toward other adjacent installations and systems can occur. Some manufacturers publish its own recommendations for installation of their frequency converters, which specify the suggested configuration of converters' output circuit that allow avoiding EMC violation problems. Majority of these recommendations is related to motor feeding cable specification and wiring style, especially grounding connections.

The problem is that the length of motor cable and its arrangement depends substantially on requirements of particular application and cannot be precisely predicted or fixed at the design stage of ASD. Particular parameters of motor cable can influence significantly overall EMC performance of ASD, which can necessitate using an extra filtering technology at the output and input sides of FC [21,22]. Some typical filtering solutions correlated with the length of motor cable are also recommended by manufacturers [23,24]. Unfortunately, even strict accordance to manufacturer's recommendations quite often is not sufficient to ensure lack of interference in electrical systems containing ASD. Usually each ASD installation requires the use of additional measures to maintain generated conducted emission at acceptable level.

The most frequently occurring EMC problems in control systems with ASD are usually associated with

- high levels of common mode (CM) currents at converter's output caused by wire-to-ground parasitic capacitances,
- overvoltage transients at motor terminals as a result of impedance mismatch,
- excessive transfer of CM currents from converter's output side toward power grid,
- high AC motor internal CM currents damaging motor bearings,
- stray HF current circulating in surrounding grounded components as a potential source of interfering effect for other systems,
- high levels of radiated emission close to motor cable route, easily coupled to other systems, and
- significantly elevated narrowband conducted and radiated emission within selected frequency bands as an effect of motor cable length.

Intensity of these effects is difficult to predict accurately using known procedures of radio frequency interference (RFI) filters design recommended for converters' load side, and it is therefore hard to avoid. There are number of issues that make procedures used for designing RFI filtering at the output side of FC particularly difficult. The most significant of them are related to

- insufficient standard recommendations related to converters' output side, motor windings, and motor cables;
- difficulties with accurate determination of parameters for models of AC motor windings and motor feeding cable in a wide frequency range;
- lack of manufacturer's specification and severe difficulty with experimental determination of parasitic parameters of frequency inverters—especially internal stray capacitances between the energized components and ground; and
- possible resonance interactions between motor windings, the feeding cable, and output filters in HF range.

Fourth, conducted emission at the output side of frequency converter of ASD is not directly limited by current standard recommendations. If the grid-side conducted emission of ASD is maintained within the required limits, the output-side filtering is very often applied only in case of appearance of EMC problems in installation at the commissioning stage, very rarely at the design stage. It is a result of the fact that there are a number of ASD applications functioning successfully without any output filtering applied [25,26]. In contrast to other applications with power electronics converters, in ASD motor cables connected to output sides of frequency converters are very often placed along the same cable trays as other power cables. Such arrangement of motor cables results in the creation a propagation path that enables efficient coupling of output-side-originated conducted emission of frequency converter directly toward power system with bypassing grid-side filters of the converter [27,28]. Apart from conducted emission that can be injected by the ASD motor feeding cable directly into power grid by means of crosstalk phenomena between nearby power cables, there is also often encountered interference in nearby placed control cables, including connections of the speed control system of the ASD itself [29–31].

Fifth, in contemporary power grids, there are already many situations where a significant number of ASDs are used and this trend is increasing continuously. In such electromagnetic environment with high levels of electromagnetic emission generated by ASD, interference issues more often occur. Future power grids are expected to be developed toward smart grids in which advanced measurement and control technologies will be used and therefore the significance of electromagnetic emission and immunity levels of electrical devices in systems is also expected to increase [32–34]. The foreseen increase of threats of EMC in the future electrical systems may be associated with at least two trends already observed [35,36]:

- More electric power is converted using static converters, including ASD, at different levels of power grid: generation, transmission, and distribution, which will presumably increase overall levels of harmonic emission, even if standardized limitation for individual devices will be fulfilled [37–39],
- The increasing quantity of measuring and communication devices are widely used in order to monitor and control optimal energy-saving power flow, which can be harmfully influenced by electromagnetic disturbances originating from neighboring high-power static converters [40,41].

1.3 Essential EMC Problems of Integration of ASD with the Power Grid

Contemporary problems with integration of ASD with the power grid (PG) are predominantly related to its unintentional electromagnetic emission in various frequency bands [42,43]. EMD, as any electromagnetic phenomenon that may negatively influence the performance of other devices, are generated by any voltages and currents varying in time. Its level and spectrum content depend on the magnitude of changing voltage and the speed of change. In the last decade, the speed of change of signals occurring typically in ASD increased significantly due to successful development of power electronics transistor technology that allows switching higher currents and higher voltages in shorter time [44,45]. These capabilities result positively in significant increase of converted power at higher efficiency, but unfortunately also negatively in higher electromagnetic emission in a wider frequency range.

In ASD, electromagnetic disturbances are generated by different components and therefore variously and specifically distributed over the frequency spectrum. EMD, depending on its spectral content, can influence other devices and systems in different ways. First, EMD propagation paths are strongly related to its spectral content and, second, interfered device's susceptibilities highly depend on frequency of disturbing signals [5,46]. Over the years, many standards have developed specifications of electromagnetic emission and susceptibility characteristics for different devices in specific frequency ranges that are tightly correlated with particular phenomena that may disturb other devices [47–50].

According to the current standard definitions, electromagnetic emissions are usually classified into four categories based on its two characteristic frequency range: 9 kHz and 30 MHz. The frequency range above 9 kHz has been well established since long time as radio frequencies (RF) and most of EMC issues localized primarily in this range are named as electromagnetic interference (EMI). The frequency 9 kHz is also defined by IEC 60050-161 standard as frequency limit for low frequency (LF) band and high frequency (HF) band

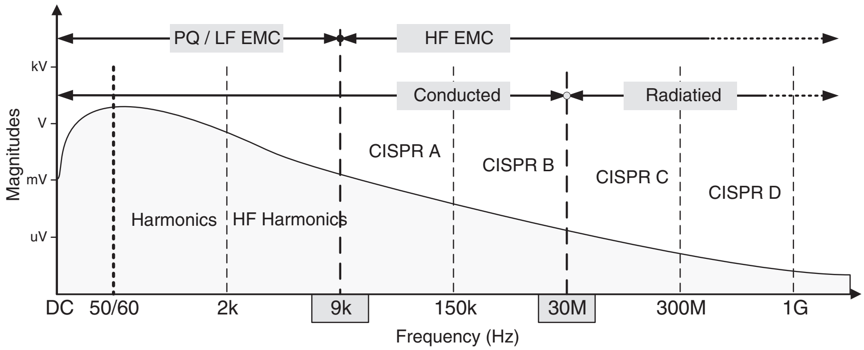

Figure 1.1 Electromagnetic emission frequency bands defined by PQ and EMC related standards.

recommended for categorization of phenomena in the field of electromagnetic compatibility (Figure 1.1).

The second limit of 30 MHz categorizes EMC phenomena for conducted emission below 30 MHz and radiated emission above 30 MHz. This split is based on the assumption that in majority of typical cases of unintended emission for frequencies lower than 30 MHz, the predominant part of electromagnetic energy is transferred by conduction via cable connections or other conductive components. Above 30 MHz, the dominating part of electromagnetic energy is propagated through space in the form of electromagnetic waves (Figure 1.1). EMD and EMI issues in frequency range below 9 kHz are usually called as low-frequency EMC phenomena with particular emphasis on harmonic distortions below 2 kHz, specified by total harmonic distortion (THD) factor that is one of power quality (PQ) index. In the frequency range between 2 and 9 kHz, the method of grouping harmonic distortion within 200 Hz wide subbands is already proposed in some standards related to high-frequency harmonic distortion limitations in power grids, for example, IEC 61000-4-7.

In general, despite some specific cases, magnitudes of EMD generated by typical power electronic applications decrease with frequency (Figure 1.1), starting from several percent of nominal RMS values of grid voltage or current within frequency range close to the grid frequency and reaching much smaller levels of only microvolts or microamperes for upper frequency range of conducted EMI band, close to 30 MHz. Unfortunately, even so low voltage and current amplitudes can be actually harmful, disturbing, and difficult to eliminate because of relatively high frequency that results in easy propagation by means of omnipresent parasitic couplings [51,52].

Currently, ASD applications are considered as one of the most disturbing sources of electromagnetic emission in a wide frequency range, from frequency of power grid up to several of megahertz. Wide spectrum and high levels of EMD

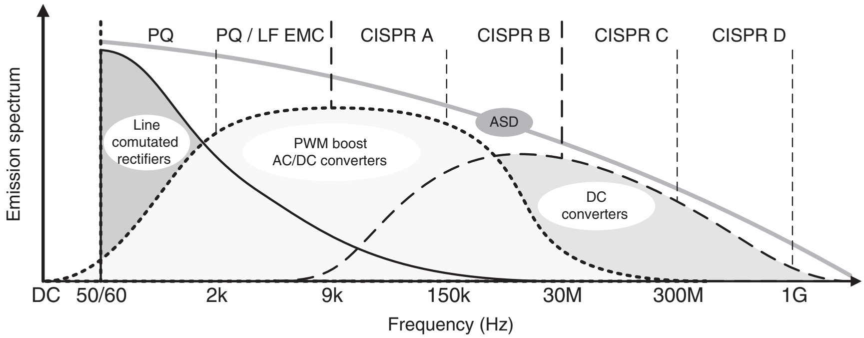

Figure 1.2 Characteristic emission spectra of typical power electronic converters commonly used in contemporary applications.

emission require to use multiple filtering techniques applied simultaneously in individual frequency subbands to reduce emission in troublesome applications to the levels accepted by standards or immunity of particular applications.

First, grid-side AC/DC converters used in ASD of low and medium rated power are in majority diode-based rectifiers. High levels of harmonic distortions in frequency range of up to 2 kHz by diode rectifiers, are well known as one of the reasons of power quality (PQ) degradation in power grids. To reduce that problem, controlled rectifies are introduced, which are based on thyristor or transistor technology. They allow limiting efficiently harmonics emission in frequency range below 2 kHz, although they simultaneously increase significantly emission in higher frequency ranges, up to few hundreds of kilohertz [53,54]. This technology is used in ASD as PWM boost rectifiers for individual drives or common DC bus ASD and as active filtering for multiple nonlinear loads. Simplified spectral differences in emission characteristics of different types of static converters are presented in Figure 1.2.

Second, ASD's output inverter, usually IGBT transistor based, generate high levels of EMD similar to DC/DC converters in HF conducted EMD frequency range of 9 kHz up to 30 MHz that can easily propagate toward the power grid through internal DC bus connections. This conducted emission can be limited using filters for radio frequency interference (RFI) [54–56].

Third, the load of FC in ASD is very exceptional in relation to classic DC/DC power electronic converters. It usually consists of extraordinary long motor feeding cable connected directly to converter terminals and thus can significantly influence the resultant ASD emission. There are two specific and critical effects of high-level EMD generated at output side of FC that are difficult to eliminate for solving EMC problems in applications with ASD:

- High levels of radiated emission nearby motor side of frequency converter, AC motor, and along motor cable that pollute electromagnetic environment and can be easily coupled to nearby located systems by means of near-field couplings [57–59].

- Increased conducted emission at grid side of FC caused by transfer of conducted emission generated at motor side of FC to the power grid through DC bus connection and parasitic couplings inside FC [54,60,61].

Both of these effects are related to HF voltage transients generated at converters output terminals, in motor windings, and in motor cable due to rapid voltage changes and impedance mismatches between converter, motor cable, and motor windings.

Finally, as it is shown in Figure 1.2, ASDs can generate significant levels of EMD in frequency ranges, primarily associated with different types of static converters, that can also be extra increased because of interactions of converter output with relatively large-scale external output circuitry, motor cable, and motor windings. Precise prediction of those HF interactions is difficult at converter's design stage, because broadband parameters of motor winding and motor cable can vary significantly in each particular application. Type of motor, type of feeding cable, and especially motor cable length and its mutual arrangement in relation to other components can be the most decisive factors.

Most of EMC and PQ issues appearing in an ASD can be divided into two categories: related to meeting of EMC standards or other regulations and directly resulting from susceptibility to other systems. Standard regulations are focused mainly toward protection of power grid against injection of excessive conducted emission and preservation of electromagnetic environment against radiated emission levels that can be harmful for electrical equipment and also living creatures. These problems are usually solved by using power lines filtering methods used in radio frequency range and device components shielding, often with significant efforts. Problems with internal EMC are usually much more challenging and require to minimize generation of EMD at its source that is essential for devices or systems themselves, because it allows minimizing external filtering and shielding demand.

This approach can be particularly effective for solving EMC problems in an ASD because internal compatibility of systems that include ASDs are often critical and also its external emission can be considerably limited by lowering internal emissions.

Essential part of the ASDs that is very critical for its internal and external EMC is FC load circuit that can be very influential and cannot be specified in details by the FC manufacturer. The FC load, such as AC motor windings and feeding cable, has to be configured individually by the ASD end user and can change significantly its final emission characteristic. There are some helpful recommendations known for designing inverter's output circuits delivered by FC manufacturers; nevertheless, application of these principles is sometimes difficult and cannot entirely guarantee the avoidance of all possible negative effects of FC load. Particular application requirements, which result from variable cable length, its layout, and parameters of motor winding and cable can change EMD emission of an ASD significantly.

Motor feeding cable and its interactions with motor windings in frequency range of megahertz can induce negative effects, for example, elevated conducted and radiated emission, excessive CM currents flow, bearing currents, and elevated exposure of motor windings to overvoltages [62–64].

Nowadays there are many investigations carried out in order to find efficient modeling method that allows estimating potential EMC problems in ASD application at the design stage. Effectiveness of wide-band modeling of ASD is essentially related to the adequacy of used models of all system components. Wide-band models of typical ASD components, adequate in conducted EMI frequency range, are usually relatively complex, because they require to take into account parasitic couplings that cannot be neglected in high-frequency bands. More accurate models of ASD components usually require much more efforts for identification of its parameters, so the main problem in wide-band modeling is the trade between model adequacy and its parameters identification overheads. On the other hand, the use of simplified models usually limits significantly a frequency range within which its adequacy can be accepted [65,66].

1.4 Scope of the Book

The objective of this monograph is to present the state-of-the-art analysis of undesirable high-frequency phenomena accompanying AC motor speed control by using voltage source inverter with PWM modulation pattern. The major part of this book is focused on the proposed new approach for wide-band analysis of AC motor with feeding cable, using simplified circuit models in frequency range of conducted emission up to 30 MHz. Theoretical analyses presented in this book have been compared with results obtained by experimental investigations carried out for selected types of low-power ASD applications. The new methods proposed for wide-band analysis of output circuit of frequency inverter in wide frequency range are highly focused on reasonable balance between modeling adequacy, model complexity with its parameters identification efforts, and computational overheads of simulation analysis.

In Chapters 1 and 2, the sources of high levels of conducted emission generated in ASDs are identified. In these chapters the fundamentals of EMI generation phenomena in switch-mode static converters are described and discussed. Analytical and graphical methods of emission spectra estimation are discussed based on the comparison of results obtained analytically with those obtained experimentally. The problem of model structure complexity and difficulties in identification of its parameters is underlined in relation to the achieved accuracy of attained results.

In Chapters 3 and 4, propagation phenomena of EMI generated by FC into the power grid are described and explained based on theoretical background and results obtained experimentally for exemplary low-power ASDs. Crucial parasitic capacitive couplings as an essential propagation mechanism are specified. In these chapters, the key impact of EMI generated at output side of frequency converter on input-side common mode currents injected by an ASD into the power grid is underlined. Parasitic capacitances of internal DC bus link in FC are pointed out as a foremost EMI propagation pathway between converter's output side and grid side.

In Chapters 5 and 6, methodology of modeling conducted emission generation and propagation in ASDs is presented. In these chapters, new simplified wide-band models of AC motor windings together with motor feeding cable are proposed and verified by simulation analysis and experimental investigation. New approach, based on time domain transient analysis, is proposed and discussed in relation to other methods that are relatively more complex, require more laborious procedures of model's parameters identification, and result in not very reliable final effects.

Finally, in Chapter 7, the influence of wide-band behavior of FC load, AC motor windings, and motor feeding cable on grid-side conducted EMI emission levels are analyzed theoretically using the proposed models. The obtained simulation results are compared with those obtained experimentally for the evaluated, typically used low-power ASDs with a diode rectifier as grid-side AC–DC converter. In this chapter, the applicability of the proposed method for estimating the influence of AC motor and feeding cable parameters on the overall EMC performance of the ASD is presented.

1.5 EMC-in-ASD Related Assumptions, Definitions, and Naming Conventions

Nowadays many different types and configurations of ASDs are in use. The used technologies include voltage or current source inverters, carrier PWM, or more advanced modulation strategies [67,68] with six or more pulse diode rectifiers as an AC–DC input converter [69], PWM boost AC–DC input converter [70], two levels or multilevel output inverters [71,72], integrated input and/or output LF filters and RFI filters [73,74], different motor winding configurations [75], various motor feeding cables [76,77], and different power electronics switches [78]. With the more advanced technology with more optional components applied, for example, RFI filters, the analysis of EMC issues in ASD becomes more and more complex. However, it is rather difficult to analyze EMC in detail in even relatively simple circuits.

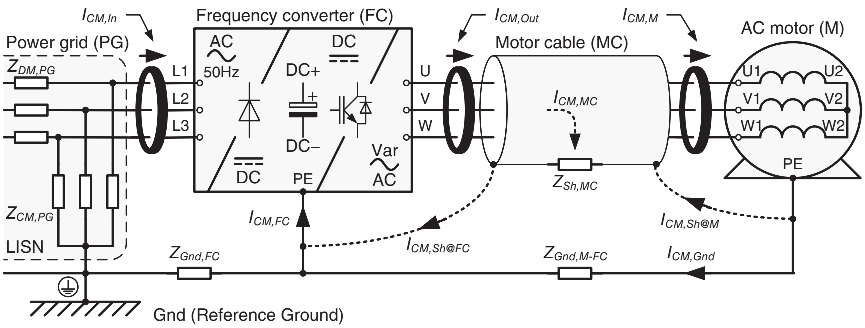

Figure 1.3 General configuration of grid-connected ASD and EMC-related naming convention.

Investigations presented in this book are primarily concentrated on EMC-related phenomena that take place at output side of frequency converter. Therefore, the configuration of the evaluated ASD has been chosen with preferences for maximum simplification of analyzed matter, especially those that are not directly related to investigated issues. The applied simplifications are focused mainly on elimination of external filtering components and using as simple AC–DC grid-side converter as possible, to avoid interactions in HF range that can significantly interfere investigated issues.

Theoretical analysis and experimental test presented in this book have been done for relatively simple ASD system consisting of

- three-phase full-wave diode-based rectifier,
- VSI inverter build as three-phase bridge based on integrated IGBT module,
- externally accessible DC link bus with capacitive and inductive filtering,
- three-wire-shielded motor feeding cable, and
- low-voltage four-pole AC motor with star-connected windings and floating star point.

The general configuration of evaluated ASD is presented in Figure 1.3 where the most significant details associated with its EMC performance are specified. The power grid (PG) is usually modeled by differential mode impedances $Z_{DM,PG}$ and common mode impedances $Z_{CM,PG}$ that represent line-to-line and line-to-ground frequency-dependent impedance characteristics seen from ASD input terminals. Unfortunately, values of these impedances are difficult to identify thoroughly, especially in a wide frequency range because they

- depend significantly on frequency band,
- depend on the localization of connection point to power grid,
- are time variable due to the power system load fluctuations, and
- can be influenced by loads connected locally to the power system.

The troublesome influence of the power grid impedance variations, which can change measurement results, can be minimized by the use of standardized line impedance stabilization network (LISN), which is recommended by conducted emission measurement procedures defined in standard regulations. The essential matter for experimental evaluation of EMC issues is a reference ground. In ASD it is a problematic issue because FC and AC motor are usually bounded to ground; nevertheless, these bonding connections cannot be considered as zero impedance connections, especially in HF range. Therefore, for presented analysis, the main grounding point of LISN was used as reference ground, despite that the impedance of ground connection of LISN to FC has been minimized efficiently in the whole frequency band of conducted EMI.

Reliable grounding of ASD components—like FC, AC motor, and motor feeding cable shield—is required primarily for safety reasons; this requires sufficient current capacity to prevent the buildup of hazardous voltages at all accessible conducting parts of installation. The impedance characteristic of grounding connections in HF range is one of the most important factors influencing reduction of conducted and radiated emission of ASD. Therefore, grounding connections, especially between FC and AC motor, should be designed to minimize impedances of grounding loops in HF range. One of the possible effective solutions is the use of shielded motor feeding cables with purposely designed shield structure with added extra returning wires to achieve beneficial impedance characteristic within the widest range of frequencies.

The majority of analysis presented in this book are focused primarily on CM currents distribution in ASD; therefore, a number of CM currents and impedances categories associated with them—presented in Figure 1.3—are defined as follows:

$[I_{CM,In}]$	input side CM current of FC that is injected into the power grid by ASD
$[I_{CM,Out}]$	output side CM current of FC that enters motor feeding cable
$[I_{CM,M}]$	motor CM currents that flow through parasitic capacitances of motor windings toward the grounded stator
$[I_{CM,MC}]$	CM current of motor cable, a part of total CM output current of inverter that flows through parasitic capacitances of motor feeding cable wires and shield
$[I_{CM,ShM}]$	CM current returning back from motor to shield of motor feeding cable
$[I_{CM,Gnd}]$	CM current returning back from motor to FC by ground connections other than motor cable shield

$[I_{CM,ShFC}]$	CM current returning back to FC by motor feeding cable shield
$[I_{CM,FC}]$	total CM current of FC
$[Z_{CM,PG}]$	CM impedances of power grid
$[Z_{DM,PG}]$	DM impedances of power grid
$[Z_{Gnd,FC}]$	impedance of grounding connection between reference ground (Gnd) and FC
$[Z_{Gnd,M-FC}]$	impedance of grounding connection between motor and FC excluding cable shield
$[Z_{Sh,MC}]$	impedance of motor feeding cable shield

Common mode currents commonly encountered in ASD are circulating in two fundamental loops presented in Figure 1.4. From the perspective of FC, these two primary CM current loops are usually named as input side loop $I_{CM,In}$ and output side loop $I_{CM,Out}$. Both of CM currents depend on internal parameters of FC, which form a main coupling path between these two loops. The input side CM currents are additionally influenced by CM impedances of the power grid and grounding connection between FC and the power grid. The output-side CM currents are influenced by CM impedances of motor windings and feeding cable. Both of CM currents $I_{CM,In}$ and $I_{CM,Out}$ are always in part flowing through parasitic capacitive coupling that exists in FC, motor, and motor feeding cable that is indicated by dotted lines. Furthermore, two components of output CM current of the FC $I_{CM,Out}$ can be distinguished : $I_{CM,M}$—the most remote, flowing through motor windings, and $I_{CM,MC}$,—flowing in a smaller loop, through motor feeding cable only (Figure 1.4).

Based on the CMC distribution presented in Figures 1.3 and 1.4, it can be noticed that

- total CMC of FC is a sum of input CMC and output CMC (1.1) (Figure 1.3):

$$I_{CM,FC} = I_{CM,Out} + (-I_{CM,In}) \tag{1.1}$$

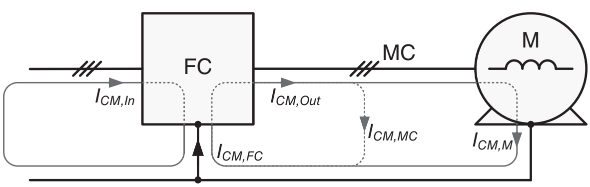

Figure 1.4 Fundamental CM currents loops in ASD.

- output CMC of FC is a sum of motor cable CMC (smaller loop) and motor CMC (larger loop) (1.2) (Figure 1.3):

$$I_{CM,Out} = I_{CM,MC} + I_{CM,M} \tag{1.2}$$

- motor CMC can return back to FC through cable shield grounding connection and by other motor grounding connections that usually exist (1.3) (Figure 1.3),

$$I_{CM,M} = I_{CM,ShM} + I_{CM,Gnd} \tag{1.3}$$

- output CMC of FC is also a sum of CMC returning back through motor cable shield and by other motor grounding connections that usually exist (1.4) (Figure 1.3).

$$I_{CM,Out} = I_{CM,Sh@FC} + I_{CM,Gnd} \tag{1.4}$$

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