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PhD Yearbook | 2020

DOCTORAL PROGRAM IN ELECTRICAL ENGINEERING

Chair:
Prof. Gabriele D'Antona

The main objective of the PhD Program is to allow a direct, prompt and efficient involvement of PhD graduates in academic and non-academic research and development bodies. A PhD in Electrical Engineering has a solid basic knowledge of applied mathematics and physics. This is essential, particularly for handling and understanding advanced tools and methods as well as for proper modelling, analysis and design of electrical engineering applications, with particular regard to power applications. A PhD in Electrical Engineering well knows methods and applications in the main disciplines of Basic Electric Circuits and Fields, Power Systems, Electrical and Electronic Measurements, Converters, Machines and Electrical Drives.
The most important part of the PhD program is the development of the research that will be the core of the PhD dissertation.
The main research areas are:
A) **Electric Circuits and Fields**: This area is intended to provide the basic knowledge of methods in electrical engineering for power applications. PhD students are specifically trained to develop critical ability and innovative approaches. The training method encourages the development of discussion and debate skills in a team environment.
The main research and training subjects are: Nonlinear networks and periodic time-variant networks; Analysis of three-phase and multiphase systems; Switching circuits; Electromagnetic field equations; Electromagnetic field numerical analysis; Electromagnetic compatibility; Design techniques devoted to electromagnetic compatibility
B) **Power Systems**: A PhD in the field of Power Systems deals with the following subjects: electrical energy production (e.g., frequency and voltage control, protections, renewable energy sources, Dispersed Generation, Microgrids); electrical energy transmission (e.g., power system analysis, real and reactive power optimization, security and stability, integration of renewables); electricity markets (e.g., models, ancillary services, regulations); power quality and Smart Grids (e.g., harmonic distortion, active filters, UPS, interruptions and voltage dips, DC distribution).
C) **Electric machines and drives**: This research field is strictly related to the rising demand for improved machine and converter performance, in terms of low price, efficiency, robustness, dynamic response and drive control. This need leads to device optimization and better design and testing criteria. Moreover, a system approach is required for accurate integration of technical and economic aspects for final application.
The main subjects in this field are: Use of new materials; Novel magnetic structures; Methodologies of model development for design and operating analysis; Optimization procedures; Use of finite elements code, simulation programs and environments for device study; Control system definition both on the device and system side.
D) **Measurements**: This research field concentrates on the fundamentals of metrology, particularly with respect to characterization of modern measurement systems based on complex digital signal processing structures. Some of the main subjects of study are: measurement methodology as it relates to power systems, including medium and high voltage systems and components, as well as both digital and analog signal processing. Methodologies and measurement systems associated with industrial automation and, in particular, microelectronic sensor applications, distributed structures and advanced methods and algorithms for maintenance-oriented diagnosis of complex systems are investigated in detail.
After graduation, PhD are typically employed at:
- Major research centres;
- R&D departments;
- Power generation, transmission and distribution firms;
- Engineering consultant offices;
- Metrology reference institutes and certification laboratories;
- Process and transport automation areas.

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CARRIER SIGNAL CONTROL OF SINUSOIDAL PWM FOR HIGHER QUALITY WAVEFORMS FOR MM AFPMSG IN WECSs

Khaled Elshawarby - Supervisors: Prof. Antonino Di Gerlando, Prof. Roberto Perini

The thesis proposes a complete improved wind energy conversion system using group of two level converters instead of MLI. The machine understudy is a multi-modular axial flux PMSG which is directly driven by the wind turbine. Each module of the machine is connected to a two-level converter with sinusoidal PWM. All the machine-side converters are connected either in series or parallel depending on the dc voltage level (i.e. parallel configuration for on-shore and series configuration for off-shore applications). The schematic of the system is displayed in Figure 1. Based on a detailed derivation, a phase shift is applied between the carrier signals of the neighbouring converters in order to cancel out targeted harmonics in the dc current, voltage and electromagnetic torque. This technique is called Sequential Command. Figure 2 presents the THD% of the torque for the normal SPWM (T_{e1}), two (T_{e2}), three (T_{e3}) and four (T_{e4}) modules with sequential command respectively. Two important conclusions can be made from figure 2: First, the high accuracy of the derived analytical expressions in comparison to the simulation results and second, It can be seen as a general observation that, by increasing the number of modules, the THD% of the overall quantities decreases.

Different aspects are analysed in this system: namely the control aspects of the converter both in case of parallel and series configurations. Moreover, a comparison between the proposed system and the Neutral point clamped (NPC) multi level converters is introduced. The proposed conversion scheme offers high redundancy, reliability and lower harmonic content compared to the multi-level converters NPC at the expense of higher converter losses due to the increased number of switching instants.

The grid-side converters are a mirror image to the machine-side converters with the sequential command sinusoidal PWM. A proposed design for a multi-winding transformer is developed. The transformer design and modelling aspects are considered, and its performances are estimated, considering inverter command parameters, current waveforms, copper and core losses, accounting for the effects due to harmonics.

Finally, torsional vibration problems are investigated for the machine-wind turbine drive train. Torsional mitigation technique based on the control of the carrier phase angle in the sinusoidal PWM is presented supported by analytical justification, simulation and experimental results. Figure 3 presents the experimental results at resonance by inverting the carrier signal and the corresponding effect on the carrier signal. The angular deflection although in resonance remains in a confined between fixed envelope thanks to the mitigation method proposed.

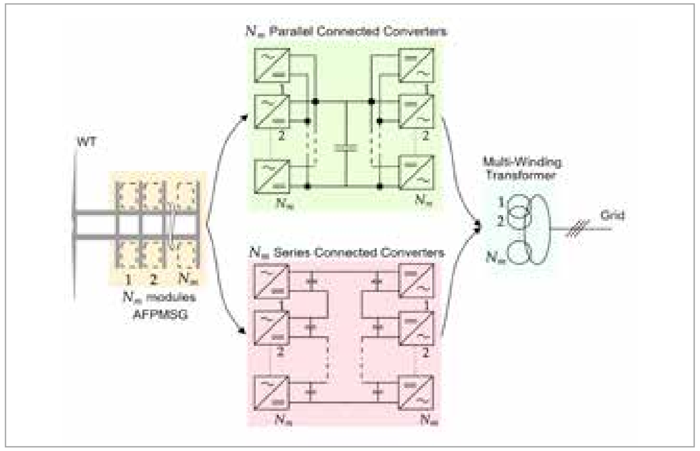

Fig. 1 - Overall schematic of the proposed WECS

Another method suited for existing ill-designed systems to avoid torsional vibrations excitation is also explained consisting of using a variable modulation frequency ratio in order to avoid torsional excitations.

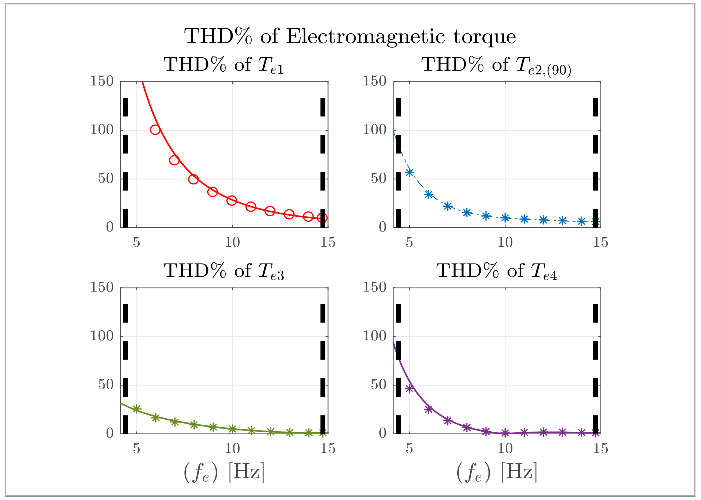

Fig. 2 - Electromagnetic torque THD% of the four cases: THD% Te1, Te,(90), Te3 and Te4. Continuous lines: theoretical results, Markers: simulations results

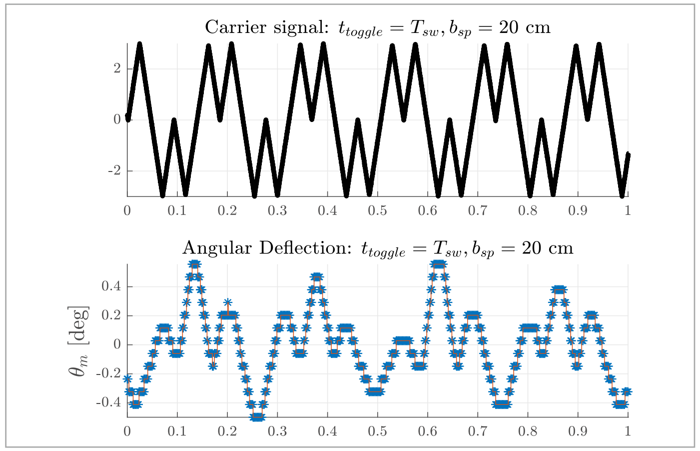

Fig. 3 - Experimental Results: Carrier signal and angular deflection of the rotor shaft in degrees at Carrier signal inversion every $t_{toggle} = T_{sw}$

FDTD FORMULATIONS AND NODE-TO-NODE ADMITTANCE FUNCTIONS MODELS FOR TIME DOMAIN ANALYSIS OF FREQUENCY DEPENDENT LOSSY MULTI-CONDUCTOR TRANSMISSION LINES

Youpeng Huangfu - Supervisors: Prof. Luca Di Rienzo, Prof. Shuhong Wang

The multi-conductor transmission line (MTL) model and the computational approaches are extensively applied for the state assessment in the switching-like pulse electromagnetic (EM) applications. They provide theoretical basis and analysis methods for the effective solutions of the unexpected challenges, such as signal integrity, crosstalk as well as the electromagnetic compatibility (EMC) problems. Generally, the per-unit-length (p.u.l.) distributed parameters, such as the resistance, inductance, conductance, and capacitance are frequency dependent quantities. The time domain solution is the most fundamental and intuitive representation for the MTL equations. As a consequence, the research of the time domain MTL solution to accurately and efficiently represent the frequency dependent parameters is of great theoretical significance and engineering importance.
The frequency dependent features of the resistance and the internal inductance are mainly due to the skin and proximity effects. The existing Finite Difference Time Domain (FDTD) mehtod is able to include the skin effect, while the influence of the proximity effect is subject to a further investigation. Preliminaryly, in this research, the FDTD formulations for a two-conductor transmission line (TL) and an MTL are systematically derived for the inclusion of the skin and proximity effects, respectively. They are essentially on the basis of an improved two-conductor TL model and an improved MTL model, which are characterized by the partial resistances and the partial inductances. Compared with the case of a two-conductor TL, the resistance and the internal inductance of a conductor in an MTL system are affected by the adjacent ones in the presence of proximity effects. Hence, the modeling of the resistance and the internal inductance for each conductor becomes a key problem to be solved urgently. To this purpose, an idea of coupling MTL model with the numerical solution of EM field is introduced in this research. The Boundary Element Method (BEM) formulation enforcing high order surface impedance boundary condition (SIBC) is adopted for a coupling solution to the resistance and internal inductance for each conductor (in an MTL and in a two-conductor TL). As far as the terminal representation of an MTL is concerned, the computational efficiency of the FDTD approach needs to be improved. Consequently, the Node-to-node Admittance Functions (NAFs) models are presented for this purpose. During the implementation of the NAFs model, the traditional MTL model can not be applied to extract the terminal admittance matrix (TAM). This is due to the fact that the real parts of the poles for the admittance in the TAM regarding to the reference conductor are greater than zeros after the approximation via a matrix rational approximations (MRAs) technique. This as a matter of fact leads to an unstable NAFs model. Consequently, an MTL model which is characterized by the loop resistances and the loop inductances is established in this research. In this case, the stability of the resulting NAFs model is guaranteed. The voltages of each terminal for the conductors with respect to the reference one can be accurately computed. Particularly, in the MTL model with loop parameters, the reference conductor is treated as an ideal one, so that the voltage across the two ends is zero. It is included into the voltages for the other conductors as a matter of fact. To uniquely compute the voltage across each conductor, an improved NAFs model based on the improved MTL model is proposed for a frequency dependent lossy MTL.
The main research activities and highlighted achievements are structured as follows:
(1) An improved circuit model for the two-conductor TL which is characterized by the partial resistances and the partial inductances and the relevant analysis approach are presented when the distributions of the voltage and the current at the internal points along a TL are concerned. A frequency selective partial internal impedance model is proposed based on the features of the skin and proximity effects. At low frequency range the partial internal impedance is taken as its dc value; and at high frequency range it is computed via the BEM-SIBC. Subsequently, an explicit expression of the smooth transition model for partial internal impedance is obtained from the frequency selective one with the aid of first order low and high pass filters. The TL equations with convolution scheme is detailed deduced. Subsequently, a FDTD formulation is obtained by the discretizations of the TL equations and the required convolution integral via a central difference approximation. In addition, a recursive convolution technique is adopted for a computational efficient FDTD formulation, which solves the problems caused by the direct convolution, such as the high storage requirement and the lengthy computation. The main error sources and the stability criterions of the proposed FDTD formulation are detailed discussed. Its correctness and effectiveness are validated by comparison with a reference inverse fast Fourier transform (IFFT) solution. In addition, it shows an improvement in terms of the accuracy with respect to a traditional one, which does not consider proximity effect.
(2) An improved MTL model with the inclusion of partial resistances and partial inductances is presented, which is an indirect extension for the case of a two-conductor TL. Subsequently, the coresponding analysis mehtod is described. On this basis, the MTL equations in time, in frequency as well as in Laplace domains are reformulated in matrix notations. Specifically, the increased complexities of loop resistance and loop inductance matrices are discussed in the presence of skin and proximity effects. A frequency selective internal impedance model for each conductor is obtained based on the low and high frequency approximations. Further, a solution of the transition model for loop internal impedance with different physical dimensions is investigated. The recursion FDTD formulation with recursive convolution for a frequency dependent lossy MTL is detailed derived. Remarkably, the BEM-SIBC solution is embedded into the developed FDTD program for a highly efficient field-circuit coupling scheme. Numerical studies indicate the correctness and practical applicability of the proposed FDTD formulation.
(3) In view of the terminal representation, an MTL model including the loop resistances and loop inductances with the confirmed effectiveness is presented. Two approaches are described to extract the targeted TAM for an MTL with the desired length. An explicit relation between the entries of the TAM and the admittance elements of the NAFs is well-established. The TAM is amenable to the MRAs process directly, which yields a stable rational model. Consequently, the rational model for NAFs is deduced from the one for TAM. Subsequently, a NAFs model for a frequency dependent lossy MTL is implemented with the aid of a circuit synthetization method. Thereby making the voltages of the terminals for each conductor with respect to the reference one is computable. To realize a NAFs model for a long MTL, a segmenting method is briefly introduced. Numerical validations demonstrate the correctness and effectiveness of the proposed NAFs model. Interestingly, it can be an efficient substitution for the original MTL model due to the high computational efficiency in frequency domain. Importantly, it shows improvements in terms of the accuracy and the computational efficiency against the proposed FDTD formulation.
(4) For a unique computation of the voltage across each conductor, an improved NAFs model is proposed on the basis of the improved MTL circuit model. Remarkably, it overcomes the disadvantage of the FDTD technique and the NAFs model, which can not accurately compute the voltage across each conductor. The direct extraction method is adopted to determine the modified TAM for an MTL with the desired length. Remarkably, the introduction of partial resistances and partial inductances facilitates the modified TAM can be approximated via the MRAs with a further stable rational model. Thus, by using the circuit synthetization approach, the terminal representation for a frequency dependent lossy MTL can be fast and accurately obtained. Although the improved NAFs model is evidently at the price of the increased model complexity in terms of the number of the terminals and the number of the admittance elements, satisfactory accuracy is achieved both in frequency and in time domains. It gives a similar accuracy with the NAFs model when it comes to the computation of loop voltages, and it still preserves a superior accuracy and the computational efficiency with respect to the proposed FDTD formulation. Additionally, it still significantly reduces the computational time regarding to the improved MTL model.

ADVANCED METHODOLOGY FOR STUDY OF MICROGRIDS INCLUDING POWER ELECTRONICS AND HARDWARE-IN-THE-LOOP SIMULATION FOR TEACHING AND ANALYZING ENGINEERING PROBLEMS

Yujia Huo - Supervisor: Prof. Giambattista Gruosso

Microgrid, as an essential part of future power systems, has many technical barriers due to the transition of the form of power generation. First, renewable generation usually does not possess kinetic energy storage and, its intermittent power output induces frequency transients and possible loss of stability. Second, renewable energy resources integrate into microgrids by means of advanced measuring components, power electronics devices, microcontrollers, control and communication technologies. All these changes bring about a new complexity and a new dynamic range of the study, making conventional simulation methods insufficient. Therefore, the objective of this work is to propose a methodology for microgrid study. It should provide insights into microgrid integration issues and the corresponding remedies. It is also supposed to comprise the complexity of real devices, bridging the gap between theory and reality. Finally, the role of power electronics should not be overlooked.

A controller-hardware-in-the-loop simulation platform is firstly developed in the context of microgrid. It provides a genuine testing and debugging environment for controllers in microgrids under various test conditions. The architecture of the platform is defined. Real-time simulation issues such as real-time modeling and circuit partition are addressed. The stability problems due to circuit partitioning are systematically discussed, too. Therefore, the proposed partition method not only provides enough stability margin but also reduces the computing burden of real-time simulator. This guarantees efficient utilization of simulator and permits expansion of the microgrid scale. On this platform, a multi-rate system is designed considering the tradeoff between computing burden and simulation performance.

Concerning the integration of renewable energy sources, a novel ramp-rate control method and a frequency-assisting ancillary service are proposed.

The ramp-rate control aims to mitigate the high ramp-rate of power in PV-integrated microgrids. Considering that time-varying loads have significant impact on grid frequency and their power consumption can be regulated to a certain extent in a network, the proposed control method mitigates the overall power ramps of the unpredictable PV generation and the fluctuating loads by the regulated load power consumption. Since the load compensation method performs ramp-rate smoothing, the battery energy storage system attached to the PV system undertakes the duty to restrict the excessive ramp-rate to a preset boundary. PV self-curtailment is also discussed, resulting in further reduction in battery. Several simulations are performed on a microgrid system, demonstrating the effectiveness of the proposed control strategy in limiting the power ramp-rate and its advantage over relying on only the battery energy storage system to economize on batteries. Thereafter, three control modes of PV based on load compensation are discussed with the aim of 1) assisting the load compensation method under extreme situations, 2) reducing the cost of the batteries and 3) providing ancillary service. The corresponding simulations show that applying virtual synchronous generator control succeeds in reducing the depth of (dis)charge and the number of (dis)charge cycles from a battery's perspective, and at the same time, makes it possible to enhance the robustness of frequency from grid operational point of view.

As to the ancillary service, it helps alleviate frequency transients without sacrificing the original planned power supply nor relying on extra power reserves. Different from the active power compensation by virtual inertia methods, the proposed ancillary service aims to smooth the transients of the active power consumed by loads. It is inspired by the field-oriented control of induction motor but works in the context of modern microgrid with the renewable generation being the actuators and the synchronous generator being the target. The novelty is that it requires no extra reserves and can be integrated into any grid-tied inverters. The ancillary service is explained theoretically by equations and verified in simulation. The performance is compared with that of the virtual inertia method. Even though both ancillary services can achieve improvement on frequency transients, the working principles behind them are quite distinct and thereby, the requested types and polarities of power used for the ancillary services differ as well. Finally, the efficiency of the control, regulator design and the influence of the irradiance are discussed to give comprehensive understanding of the proposed method.

In controller-hardware-in-the-loop simulation, practical issues of the control system are exposed. Real devices in the loop help understand the imperfection of physical components and at the same time, provide information for the improvement of the control system in industrial applications. This is how hardware-in-the-loop simulation distinguishes itself as a fitting validation tool for revealing problems concealed by offline simulations. The novel ancillary service mentioned before has been tested on the hardware-in-the-loop platform. The results indicate that the hardware-in-the-loop simulations not only validate the effectiveness of the proposed method and but also expose some practical issues, which cannot be observed by using offline simulations. In the test case, an abnormal reactive power flow occurred and thus weakened the performance on frequency transients. With the help of hardware-in-the-loop simulations, the intrinsic contributors of these issues were detected and the corresponding modification to the ancillary service was proposed and validated.

After that, the idea of real-time control extends to power electronics application. A power electronics laboratory based on real-time technique is developed for educational and research purpose. The development starts with laboratory planning where contents and organization are defined. The modernity is also addressed. In this phase, the organization of the laboratory is defined for the maximum flexibility and safety. Hardware design work is carried out from device level to system level with many industrial solutions generated. An IGBT modeling method is proposed for the analysis of switching dynamics and for the driver design. Corresponding software is developed in a real-time controller, including real-time control, monitor, fault handling, data handling, etc. With the developed graphical user interface, the laboratory is intuitive for education. It is an efficient tool for researchers as well. Its modularized design brings flexibility and efficiency to cover around 100 experiments. With the user interface, users feel free to configure their own control algorithms executed in a real-time control system within specialized frames for various switching power converters in different applications. They also observe the performance from the graphical user interface to understand the complex behaviors of converters. Furthermore, the potential expansion into power-hardware-in-the-loop application will allow researchers to study power converters and microgrid issues in a more rigorous way.

In this thesis, advanced methodology for study of microgrids including power electronics has been proposed to deal with the technical challenges in microgrids. It utilizes hardware-in-the-loop technique to mitigate the drawbacks of conventional study and test of microgrids. Concerning the integration of RESs into microgrids, this work proposes two control algorithms for renewable generation systems. In order to include the power electronics part, which is essential in microgrids, a real-time controlled power electronics laboratory has been developed as well. In summary, this work provides a complete toolkit for teaching and analyzing engineering problems.

WORST-CASE AND STATISTICAL PREDICTION MODELS FOR RADIATED INTENTIONAL ELECTROMAGNETIC INTERFERENCE

Tao Liang - Supervisor: Prof. Giordano Spadacini

The modern society heavily relies on the operation of electrical/electronic systems, whose functional safety and reliability are continuously challenged by harsh electromagnetic environments (EMEs). Although this issue has been recognized as early as the development of atomic weapons in the World War II, it was not until recent decades that common awareness and concerns have finally been raised due to three distinct reasons. First, the intrinsic immunity level of systems has continuously reduced due to the growing integration density and rapid miniaturization of circuit elements according to the Moore's law. Second, new technologies make EMEs more and more severe and contribute to the exhaustion of spectral resources. Third, new Intentional Electromagnetic Interference (IEMI) threats are made possible by the advancement of High Power Electromagnetic (HPEM) technology. Consequently, it is of paramount importance to offer industry-effective methods to quantify susceptibility levels so that guidelines can be proposed to assist system design and to reinforce mission-critical loads through protection strategies.

In line with this background, my doctoral research focuses on assessing the susceptibility of systems to intentionally radiated HPEM environments. The investigation starts by modeling a radiated IEMI attack as a plane-wave field-coupling problem. Specifically, a field-coupling model based on the Lorentz reciprocity theorem (exploiting full-wave simulations) is established for a linear multiport victim system, enabling a computationally efficient solution of the induced load voltages/currents at the system's ports. This model must be used in the framework of a worst-case and/or statistical assessment, since many parameters involved in the coupling link between source and victim are unknown or inherently random in a real electromagnetic attack.

Taking uncertainty into account is a major objective of the proposed analysis. The investigation is firstly focused on the uncertainty of the source of interference, since the broad standard definition of IEMI leaves infinite possibilities on HPEM field waveforms. For instance, intentional HPEM fields may encompass both narrowband waveforms having any center frequency, and ultra-wideband waveforms characterized by any spectral content, typically above 300 MHz. In this connection, the investigation of worst-case scenarios is proposed, namely, the optimization of waveforms to maximize significant figures of merit correlated to susceptibility mechanisms. Specifically, the objective functions are significant signal norms of the induced voltage (peak, energy, rectified-impulse), which are widely recognized quantities correlated to system failure or damage. It is shown analytically that in the worst-case energy scenario, the HPEM field shall be a properly tuned narrowband field, whereas in the worst-case voltage peak scenario a wideband field properly matched to the frequency response of the system is needed. In addition, it is shown that the rectified impulse of the induced voltage can be made arbitrarily large by reducing the impinging field bandwidth. An illustration of the worst-case IEMI waveforms of the impinging field is summarized in Fig. 1.

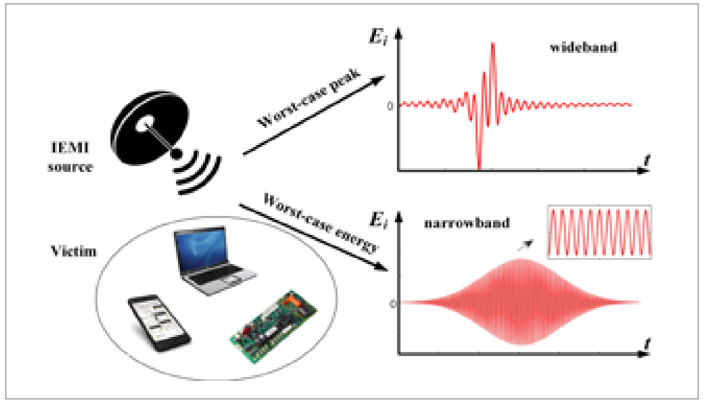

Fig.1 - illustration of typical worst-case IEMI waveforms for exciting electronic systems.

Lack of knowledge on the direction of incidence and polarization angle of the plane-wave field, and uncertainty of geometrical parameters of the system also contribute to uncertainties in the coupling link. Accordingly, the Monte Carlo method and a stochastic reduced order model are proposed to characterize the abovementioned worst-case norms through cumulative distribution functions.

The proposed assessment method is exemplified and applied to wiring systems and interconnects with the objective to unveil the impact of significant parameters (length, height, terminal impedance, shielding method, etc.). Finally, an alternative model formulation based on transmission-line theory is presented, which allows deriving analytical closed-form expressions of the worst-case voltage peak in selected canonical cases, easing and corroborating the interpretation of the impact of system parameters.

SOCIAL NETWORK OPTIMIZATION FOR ELECTRICAL AND ELECTROMAGNETIC ADVANCE OPTIMIZATION SYSTEMS

Alessandro Niccolai - Supervisor: Prof. Riccardo Zich

In recent years, the use of Computational Intelligence techniques is growing in the engineering design: methods as Evolutionary Optimization Algorithms as well as Artificial Neural Networks are becoming more common and better known. In this thesis, the design of a novel evolutionary approach for the optimization of complex electromagnetic systems has been studied: the whole optimization system architecture has been analysed with the aim to reduce the required computational time.
The optimization environment is based on two pillars: the optimization algorithms and the optimization problem. These two interact by means of two connections: the first one, from the optimizer to the problem, is composed by the box boundary condition management and the design variables mapping, while the second one is composed by the cost function. All these parts of the optimization system work together and highly affect the final result of the process.
In this thesis, Social Network Optimization (SNO) has been implemented, analysed and compared with other algorithms in both standard benchmarks and real word problems. This algorithm takes its inspiration from the information sharing process in online social networks: starting from the analysis of this interaction, SNO operators have been designed.
The algorithm working principles have been deeply investigated: firstly, an analytical model has been used to investigate the population behaviour as a function of the parameters, and then a deep parametric analysis has conducted done with a numerical approach. The results show that the numerical behaviour of the algorithm corresponds within some limits to the analytical models; an important feature has been discovered with this numerical analysis: the two most influencing parameters have their optimal values in the same area for different objective functions.
SNO has been then compared with other optimization algorithms (both population-based and point-based) on a set of 15 standard mathematical benchmarks. These tests show a very good stability of SNO performance on different problems.
Two different electromagnetic problems have been used for testing the entire optimization scheme design: the design of a beam-scanning reflectarray and the design of an electromagnetic die mold.
In the reflectarray problem, the first analysed aspect is the definition of the cost function: in fact, the antenna has several performance parameters that should be included in a single cost value. A proper selection of the weighting factors can properly drive the optimization process to the desired target.
Then, the box boundary conditions have been investigated: the traditional wall condition shows the best performance, while the closed search space results in a lower convergence rate because it creates useless oscillations in the population.
Furthermore, the aperture field method, used for calculating the radiation pattern, has been assessed with respect to a commercial full-wave simulator. The results show that the

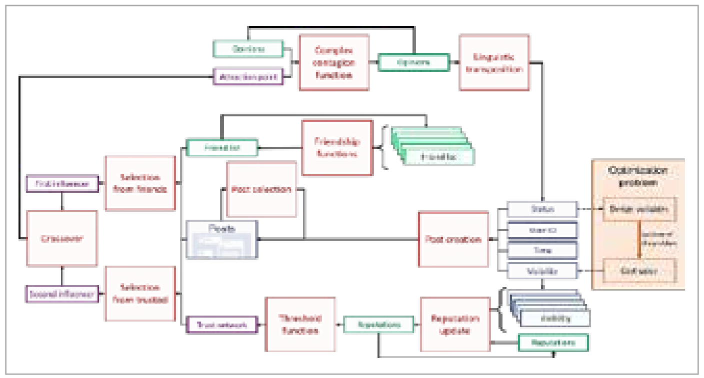

Fig.1 - Social Network Optimization operators and data structures

aperture field method is able to give a proper trade-off between accuracy and computational time.
Different SNO parameters have been analysed; in particular, the effect of the population size has been considered. The results are that a large population size guarantees a more constant convergence rate, but it requires a huge computational effort. On the other hand, a small population size guarantees a very fast convergence at the beginning that may lead to a premature convergence on local minima. The characterization of these two behaviours is important because it can be used as heuristic technique for defining the optimal population size.
After this analysis of the optimization scheme, the results of SNO have been analysed and compared with the ones of other EAs. From this comparison, SNO resulted to have a performance comparable with DE, but with lower mean value and with a much smaller standard deviation, thus confirming it as a reliable optimization approach.
The second problem analysed is a different electromagnetic design problem and it has been firstly faced using a free FEM simulator, performing several tests on the optimization scheme: as first step, the optimal population size of SNO has been analysed; secondly solutions found by SNO have been analysed for understanding the properties of the search space of the problem. In particular, the optimal solutions are very often on the boundary of one of the design variables. For this reason, a new optimization test has been run with an enlarged search space: the optimal solutions improve, but the problem appears to be more complex because an higher number of solutions are in a local minima.
Finally, a different approach has been used for defining the search domain: it has been modified iteratively at the end of a set of optimization runs. In this way the exploitation capabilities of the algorithm are increased, and the performance are improved both in terms of optimal and average solutions found.
The optimal solution has been assessed with a commercial software, the well-known Comsol Multiphysics: it results that the solution of this problem with the free FEM simulator is not accurate enough for performing the optimization. For solving this problem, and for finding a trade-off among the required computational time and the accuracy, a surrogate model has been introduced in the optimization scheme.
The Ordinary Kriging has been used because it returns also the confidence level of the prediction. This can be very useful for selecting iteratively during the optimization procedure the new sampling point from the algorithm population in order to guarantee the accuracy of the model. By using the surrogate models approach it has been possible to achieve comparable results with respect to the standard optimization with Comsol in about 40% of the required time.
The results obtained in these two electromagnetic applications show that, for achieving highly performing results with EAs, a proper design of the optimization system should be found. This is highly affected by the specific problem, but there are several common features to all of them and the proposed optimization approach was found to be suitable to properly address these aspects.

PARTIAL DISCHARGES DIAGNOSTICS: LOCALIZATION IN COMPLEX BOUNDED DOMAINS

Luca Perfetto - Supervisor: Prof. Gabriele D'Antona

Partial Discharge (PD)

A Partial Discharge (PD) is a localized electrical discharge that only partially bridges the insulation between conductors. It appears at microscopic level as consequence of high and non-uniform electrical field in insulating materials defects.

A PD can take place only if two conditions are simultaneously satisfied: there must be at least one free electron and the electric field must be sufficiently strength and long enough to ensure that this electron generates a sequence of avalanches. These conditions are mainly determined by the amplitude and frequency of electrical voltage and current; temperature, pressure and humidity also affect the PD behaviour. PD phenomenon is of particular interest in medium and high voltage electric equipment since its ageing effect on insulating materials leads to electrical failures. Hence, in order to ensure electric system reliability and safety, effective diagnostics is fundamental to detect and eventually localize PDs.

Nowadays, acoustic and Electro-Magnetic (EM) measurements are used together with the Time Difference Of Arrival or the Received Signal Strength methods to estimate the PD location. However, these methods are able to provide reliable and accurate results only in quasi-homogenous, open and very large domains (i.e., open air substations).

Ph.D. goal

The goal of this research is to develop a novel diagnostic method well suited for complex, closed and limited domains such as oil-filled power transformers, air / gas insulated switchgears and gas insulated transmission lines. These are critical and expensive electric equipment installed in power systems, which contain several parts presenting PD activity.

Ph.D. contribution

The thesis demonstrates the developed and promising solution for PD diagnostic method, which exploits a set of EM measurements together with ad-hoc numerical algorithm to reconstruct the EM field due to the PD sources in order to localize them. Subsequently, the defective component can be identified and eventually repaired or substituted.

The EM strategy in the Ultra High Frequency range (0.3 GHz - 3 GHz) is chosen because of its technical advantages in term of wide dynamic range, high sensitivity and spatial resolution. The measurements are on-line acquired by means of suitable probes, which are installed inside the electrical equipment. Once available, the measurements are processed by ad-hoc numerical algorithm to reconstruct the EM field due to the PD sources in order to localize them. The algorithm is based on a proper EM wave propagation, which describes the relation between the measured EM field and the PD source through the eigenfunctions expansion series. This powerful mathematical tool intrinsically encapsulates all the physical information such as domain geometry, propagation media properties as well as the boundary and initial conditions. This choice makes the diagnostic method very robust and accurate. In complex domains the eigenfunctions can be numerically computed, i.e., using a finite element model. Figure 1 shows the first four eigenfunctions for the domain under study computed by means of the commercial software Comsol Multiphysics ®.

Figure 2 shows the used experimental set-up used to validate the proposed method. It is composed by a medium voltage circuit (up to 30 kV) to generate repeatable PD events and a high frequency measurement system (up to 4 GHz).

Figure 3 shows the accurate reconstruction and PD localization tasks performed in the realized domain.

The main goal of this work is fully achieved. The results confirm the powerfulness and efficacy of the proposed PD localization method. The obtained theoretical and numerical tools, and experimental standpoints are of general interest for both academic and industrial technical communities and they can be used as starting point for future developments.

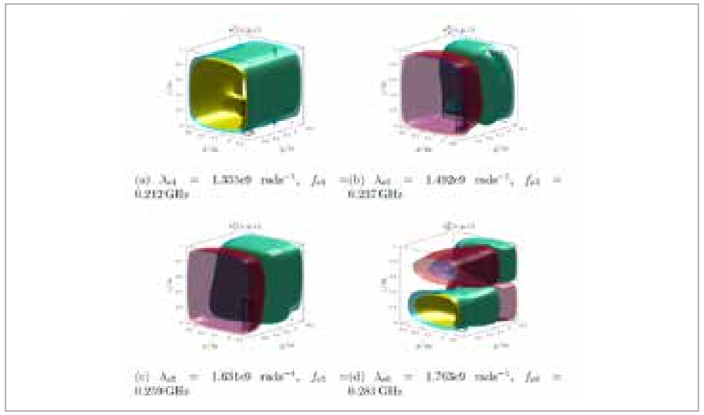

Fig.1 - Numerically computed eigenfunctions for the domain under study.

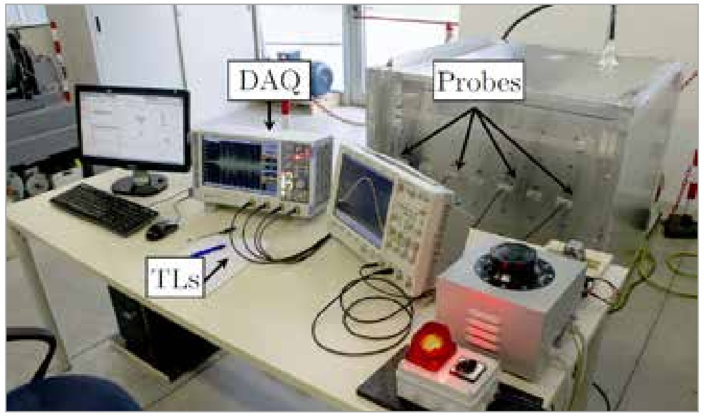

Fig.2 - Experimental setup. DAQ: Data AcQuisition (digital oscilloscope for UHF applications).TLs: Transmission Lines (coaxial cables RG-58).

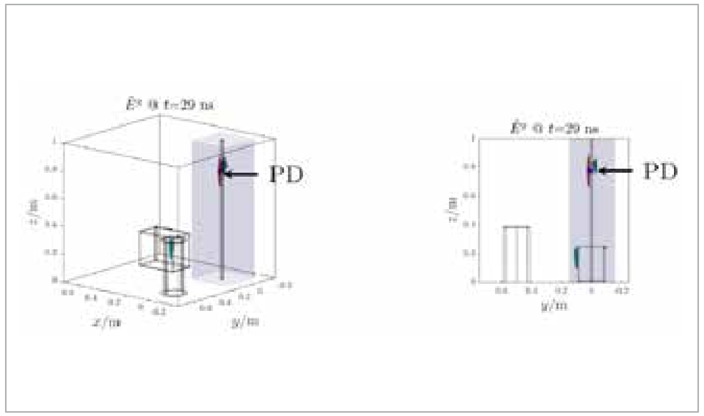

Fig.3 - Reconstructed electric field distribution inside the domain under study. The PD source is accurately localized. The highlighted rectangular parallelepiped volume around the cable is the most likely one to contain a PD source.

REAL-TIME PMU-BASED POWER SYSTEM INERTIA MONITORING CONSIDERING DYNAMIC EQUIVALENTS

Guido Rossetto Moraes - Supervisor: Prof. Alberto Berizzi

Nowadays, the energy portfolio is changing to include more Renewable Energy Sources (RES) in a search for mitigating the impact on the environment. However, the increasing penetration of RES in power systems has been bringing many challenges for Transmission System Operators (TSOs). RES-based generators are mainly connected to the grid by means of converters, that decouple the dynamics of prime movers from the bulk power system. Hence, these units do not contribute directly to the equivalent inertia of the system, and among the main consequences, larger and longer frequency excursions follow power imbalances on the grid. For that reason, estimating inertia in real-time is becoming indispensable for the overall security assessment of the system.
This thesis aims at investigating inertia estimation with the use of data coming from Phasor Measurement Units (PMUs), devices capable of acquiring measurements from the grid and providing phasors synchronized by Global Positioning System (GPS) in real-time at high sampling rates. The topic has been explored in the literature in the last few years, with many methods and solutions to estimate inertia from the terminals of single generators. However, monitoring individually each generating unit is a strong assumption taking into consideration the size of power systems and current high cost of PMUs.
Hence, estimating equivalent inertias based on the data provided by few PMUs spread on the system becomes an interesting practical research topic. The methodology used in this thesis consists in approaching some of the many challenges that a TSO may face on estimating inertia, divided according to different topics. Starting from the consideration that generators are monitored individually, to the case where areas are monitored at boundary buses, different methods were studied, and novel methods and strategies are proposed to estimate inertia in some typical situations. Different types of perturbations were considered, including loss of generation, load steps, Renewable Energy Sources (RES) integration, and also inertia estimation under normal load variations.
To test the methods, experiments with 5 different test-systems were performed, with different levels of complexity. The experiments were divided in 13 different studies, where simulations were handled using MATLAB and PowerFactory to acquire the equivalent data that PMUs could provide, and the methods were applied subsequently.
The practical assumptions of this work leaded to the development of different methods and strategies:
A novel Iterative Inter-area Model Estimation (IME) method was developed to build dynamic equivalents and deal with perturbations, adapting a method originally tailored to work with oscillations.

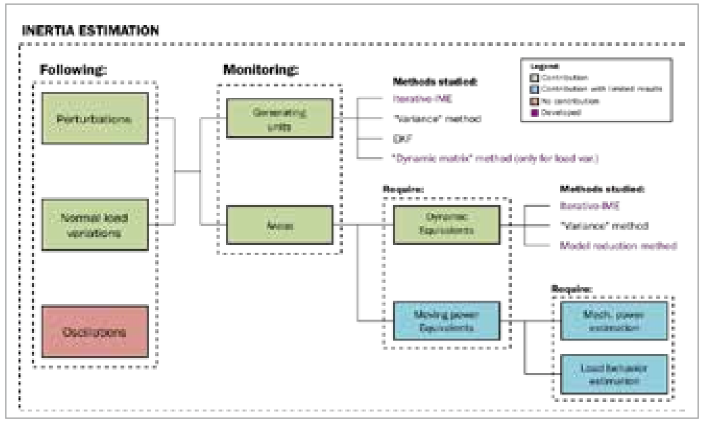

Fig.1 - Contributions of the thesis

A strategy was developed to take advantage of spread PMUs in a system, defining a study area and using the measurements available to perform estimations of the dynamics of the Center of Inertia (COI) of the referred area. The technique makes use of Ward method to reduce the system and a second method to build dynamic equivalents.
When dealing with an area that experiences an internal perturbation, the main challenge faced in this research was that the equivalent power of the referred area needs to be monitored or estimated. This condition increases drastically the requirements for practical use of the methods, such that a method to estimate the equivalent power was proposed.
Another contribution of this thesis is the study of inertia estimation in ambient conditions. A method that takes into consideration stochastic properties of load variations was proposed to identify part of the parameters of a state-space model of the grid.

Keywords: Inertia estimation, Phasor Measurement Units, dynamic equivalents.

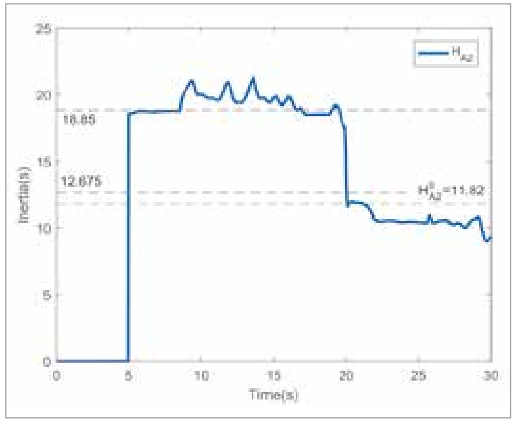

Fig.2 - Inertia estimated following a load step (t=5s) and a generator disconnection (t=20s)

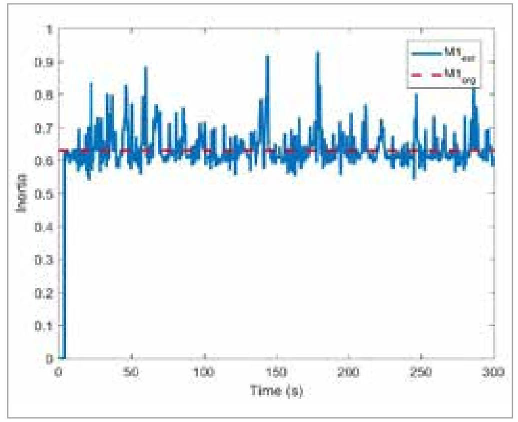

Fig.3 - Inertia estimation following normal load variations

DETERMINISTIC AND STATISTICAL MODELS FOR ELECTROMAGNETIC COMPATIBILITY AND SIGNAL INTEGRITY OF COMPLEX INTERCONNECTS

Xinglong Wu - Supervisor: Prof. Flavia Grassi

The ever-increasing need for faster and better electrical and electronic products is requiring the development of high-power density, highly dense packaging and high-speed devices. This leads to a growing demand for the design of more dense and complex transmission line systems, which increase the risk of electromagnetic interference, such as crosstalk, radiated emissions and susceptibility issues. Practical electromagnetic compatibility (EMC) measurements involving instruments, facilities and prototype devices are usually expensive and time-consuming. It is therefore of great importance to take advantage of numerical simulations for the assessment of the EMC performance at the early stage, in order to provide right-first-time designs. In this thesis, simulation techniques are introduced for both deterministic and statistical EMC analyses of multiconductor transmission lines (MTLs).

This work firstly presents a perturbative analysis of mode conversion due to asymmetries of interconnects with homogeneous media, for which closed-form or semi-analytical expressions are provided. The detrimental effects that undesired asymmetries and/or non-uniformities play on the modal voltages at the terminations of differential line (DL) circuits were analyzed by a comprehensive approach based on the perturbation of the p.u.l. parameters of an ideally-balanced and uniform reference structure. This allowed the circuit interpretation and modeling of the aforesaid non-ideal effects by means of distributed voltage and current sources included in the equivalent modal circuits of the reference DL.

Then, the method is extended to interconnects involving inhomogeneous media by introducing an *ad hoc* conceived iterative procedure in the modal domain. Specifically, an iterative perturbative approach aimed at fast and accurate prediction of DM-to-common mode (CM) conversion occurring in differential interconnects with cross-section affected by undesired asymmetry and nonuniformity resulting from imperfect manufacturing or/and layout constraints was presented. Three computational algorithms were proposed, involving different levels of approximation. The first algorithm does not exploit any approximation and requires the simultaneous refinement of both the CM and DM quantities at each iteration. The second algorithm (Level 1) exploits the assumption of weak imbalance in order to handle the two modes separately. The third algorithm (Level 2) uses the further assumption of weak nonuniformity, in order to avoid eventual CM refinements. A principle drawing of the approximate algorithms is shown in Fig. 1. The computational efficiency and prediction accuracy of the aforesaid algorithms were assessed through two application test cases, involving tapered and corrugated microstrip DLs. The discussion of these algorithms showed that the selection of these was a trade-off between computational speed and accuracy, which mainly depends on the specific characteristics of the problem under analysis. In any case, all the three algorithms result in a reduction of computational burden with respect to the traditional approach based on the line subdivision into uniform cascaded sections (UCS method). Accuracy of the proposed approaches was demonstrated by various simulations, as well as by experimental measurements.

Thereafter, the approach is further extended to the analysis of mode conversion introduced by bend discontinuities. A circuit interpretation of the phenomenon was provided in terms of lumped sources of interference included into the equivalent CM circuit. One typical circuit model is shown in Fig. 2. The obtained circuit model, assessed through full-wave simulation, allows the strict analogy between mode conversion due to bend discontinuities, trace asymmetry and crosstalk. This analogy shows that all these three detrimental effects create similar undesired induced inductive and capacitive sources in victim physical/modal circuits. By this analogy, a theoretical basis was provided and investigated for the idea to compensate the CM noises, due to the presence of the bend, by intentionally introducing asymmetric traces. An application example was provided and validated by full-wave simulation, showing that the proposed idea resulted in an overall CM reduction, while preserving DL transmission properties.

Eventually, a novel technique is proposed to speed up the statistical analysis of MTL structures. To this end, the classic stochastic Galerkin method (SGM) is hybridized with the aforesaid perturbative technique. Two different implementations are proposed. The first implementation (Coupled SGM-PT) foresees the solution of the augmented MTL problem, stemming from the application of the SGM to the original stochastic MTL under analysis, via the aforesaid perturbation technique. As a first step, the zero-order solution is obtained by solving an equivalent uniform line. Line nonuniformity is then included through distributed sources, which are accounted for by iterating and updating the solutions. Second, a *decoupled* implementation (Decoupled SGM-PT) was proposed. In this hybrid approach, new distributed sources simultaneously account for nonuniformity and variability of the p.u.l. matrices. The solution is obtained by the iterative analysis of a smaller MTL problem, having the same size as the original stochastic problem, thus achieving a better scaling and extending the efficiency to even larger random spaces. The proposed iterative implementations retain the desired high accuracy of the classical SGM, while allowing for faster computations (see Fig. 3). Indeed, the performance was assessed based on multiple MTL configurations with an increasing number of random variables (RVs), showing that the proposed decoupled perturbative method extends the applicability of the SGM to problems with a few tens of RVs, without compromising the accuracy. This is an unprecedented result for state-of-the-art SGM implementations.

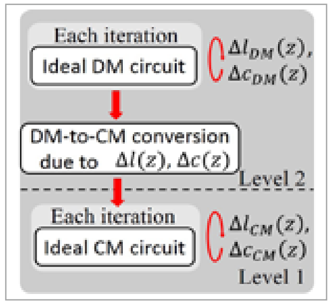

Fig.1 - Principle diagram of the approximate iterative procedures.

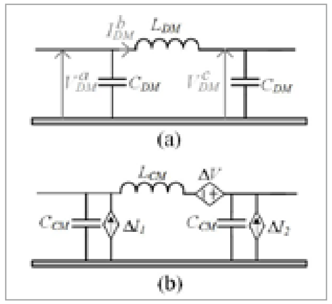

Fig.2 - Modal circuits for bend discontinuity. (a) DM circuit. (b) CM circuit

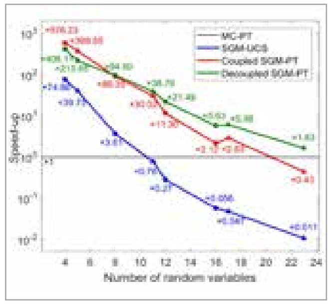

Fig.3 - Speed-up of the various SGM techniques w.r.t. the Monte Carlo analysis.