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Editorial

Recent Trends in Power Systems Modeling and Analysis

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In recent years, the explosion of renewable energy sources, the increase in the demand for electrical energy, and several improvements in related technologies have fostered research in many relevant areas of interest.

One of the richest subjects of interest is high-voltage direct-current (HVDC) transmission due to its clear advantages in terms of long-distance performance, such as reduced transmission losses, enhanced stability, and controllable operation with respect to equivalent AC installations. The basic technical–economic advantages of HVDC over AC when dealing with bulk power transfer over a very long distance, both in terrestrial and submarine applications, have been well-known since the original line-commutated converter (LCC) technology reached maturity [1]. Voltage source converters (VSCs) have further benefits in terms of dynamic support to AC systems as well as the possibility of building multiterminal DC (MTDC) networks. This potential remained unfulfilled until the introduction of modular multilevel converter (MMC) VSCs to the market, which have lowered conversion losses to reasonable values and have substantially reduced low-order AC-side harmonics. The availability of MMCs has thus prompted an enormous interest on a very broad front. To achieve a (true) meshed multiterminal DC grid, several lingering technical issues must be solved.

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First and foremost, using DC overhead lines is the only way to exploit the full potential of already-available converters in land-based applications. In turn, this requires the ability to clear overhead line faults, either by means of circuit breakers tailored for HVDC applications, providing adequate breaking current ratings at line voltage [2], or by adopting converter topologies intrinsically able to interrupt DC fault currents [3], i.e., full-bridge or similar. Full-rated HVDC circuit breakers are currently being intensely investigated, due to the higher operating losses of full-bridge MMC converters compared to half-bridge ones. DC cables are also a topic of interest, as several existing HVDC-MMC links are actually the shore connections of large offshore windfarm (OWF) clusters [4], with ratings reaching up to 1 GW at present. Further developments will depend on upscaling MMCs and the full exploitation of HVDCs' submarine cable capacity. The interest in this field is obviously compounded by the fact that cables are the only viable option for land-based HVDC-MMC transmission systems. Lastly, the MTDC concept depends on several control layers, from individual MMC submodules to overall grid voltage and energy balancing controls, which are still being actively investigated. In this regard, the emerging issue of MMC small-signal stability deserves particular attention. Of course, HVDC is also a sub-topic in the wider framework which deals with the planning and operation of large networks.

Another operation-related field of activity concerns the optimization of power flows in power systems, considering both distributed and weather-dependent electricity generation. In optimization constraints, battery storage systems, the practical and economic sizes of which are increasing, play a growing role. The energy storage in pumped hydroelectric plants is also receiving renewed attention as a means to achieve dynamic flexibility.

Rapid developments are being made in the field of power system protection, driven by the profound changes that are modifying the "historical" power system architecture, i.e., the massive spread of distributed generation with the concurrent decommissioning of the conventional large synchronous machines, and the definitive affirmation of digital multifunction relays with integrated communication features. Furthermore, this trend has created even greater interest in safe and secure power system operation (which cannot be separated from the prompt and reliable detection of grid faults).

An aspect closely related to the secure operation of power systems is the system's robustness towards overvoltages of both internal and external origin. Significant efforts have been made to overcome modeling issues, particularly in the development of a simplified model suitable for the time domain analysis of the lightning performance of overhead transmission lines.

Finally, research concerning the transient behavior of grounding electrodes is worth mentioning. Lightning strikes are responsible for damages to assets and non-scheduled interruptions to the power delivered to consumers. Power quality requirements are paramount, justifying the continuing research focused on overhead lines' lightning performance. Moreover, large, steep-front current injections in soil are associated with ionization phenomena and frequency-dependent responses for which a reliable model for general applications is not yet available.

The most interesting aspects presented in the recent literature are summarized in the following.

Multiterminal DC (MTDC) systems fault analysis and protection is discussed in several papers, either from the perspective of the system or of its components (i.e., DC breakers) [5].

Regarding fault analysis and location, the authors of [6] propose a novel fault identification method for MTDC distribution grids, adopting a Kalman filter to estimate the fault's location and resistance. The method is validated by means of real-time simulations of various fault scenarios, achieving a fast response in less than 1 ms. In [7], a faulty section location method for resonant grounding systems is developed based on a dynamic time warping distance, which allows a faulty section in various fault conditions and, notably, in high-resistance faults to be located. A backup strategy for HVDC grid protection systems based on a Rate-Of-Change-Of-Voltage (ROCOV) algorithm is introduced in [8]; it relies exclusively on the local measurement of the voltage derivative, ensuring faster fault clearing compared to similar backup systems and eliminating the need for a communication channel.

Fault location strategies are to be exploited for the prompt and selective intervention of protective devices, aiming to interrupt fault currents and limit the duration of the anomalous operation condition of the power DC connection [9]. Innovative designs of reliable protective devices have been investigated in the most recent literature. For instance, superconductive fault current limiters, constituted by the primary (ordinary) coil, the secondary superconductive coil, and the magnetic core, are discussed in [10], also suggesting a tailored design procedure. The authors describe the design options and analyze the main characteristics by means of both a 3D finite element simulation and an actual laboratory prototype. In [11], a different DC breaker architecture based on the superconductive elements' double quench is modeled in the software PSCAD/EMTDC, and the fault current interruption is analyzed for two scenarios, i.e., "larger" and "lower" fault current values. A similar study concerning the design of a hybrid (double-quench-based) DC circuit breaker is presented in [12]. Nevertheless, the research is focused on the optimal setting of the circuit parameters, highlighting their effects in terms of their ability to interrupt currents and extinction time.

Lacking operational DC circuit breakers, DC cables are the only option for HVDC-VSC transmission, but in some cases, cables might be preferred to overhead lines due to their reduced environmental impact and the rather intricate authorization processes which discourage the realization of new overhead power lines. Therefore, the industry and the research community are still seeking to improve the efficiency of cable connections for DC applications. Medium-Voltage Direct Current (MVDC) systems are also of some interest for the development of local DC grids for the connection of distributed renewable energy sources.

The authors of [13] derive a practical formula for the evaluation of the maximum permissible current for buried DC cables, accounting for the maximum insulation temperature allowed in normal operation conditions. Factors influencing this maximum value are classified as major and minor; minor factors, identified with the thermal resistance offered by inner and outer semiconducting layers, tapes, and airgaps, are found to impair the computed values of the maximum allowable current for the examined bipolar connection (±500 kV) only by 1.2%, including a third cable as a metallic return. However, the three-cable configuration, typical of AC and inherited by some DC systems, does not allow one to exploit the loadability of the cable serving as a return path. In [14], a three-phase MVAC system is converted to MVDC by maintaining the existing cables yet proposing a switching scheme to increase the power capacity of the connection by 10%. The cable connected to the positive pole carries the total current, while at the negative pole, the current is split between the other cables. The switching interval of 15 s is chosen to permute the cable connected to the positive pole.

The validity of the main assumption underlying the usual thermal calculations for buried cables (i.e., the axial symmetric distribution of temperature on the external cable surface) is assessed in [15]; it is found to be a good approximation for paired cables when equipped with an external metallic sheath, acting as an isothermal layer. The combination of the external thermal resistance (linked to the ground humidity) with the nonlinear electrical resistivity of the insulating material is a possible cause for electric field inversion within the insulation and major electrical stress for the external sheath. Therefore, the dependence of the extruded insulation conductivity on the coefficients of temperature and on the electric field is appraised in [16] in order to quantify insulation losses, contributing to the development of intrinsic and interactive thermal instability: the increasing electrical stress undertaken by the insulation may eventually lead to insulation breakdown.

Cable insulation is subjected to different electrical stresses when a constant electric field is applied compared to AC. Nevertheless, harmonics, displaying different amplitudes and frequencies, are also found in DC voltages and currents, which are intrinsic to the AC/DC conversion process. In [17], a test procedure is proposed to measure partial discharges (PDs) within a dielectric sample with a void. The sample is tested under DC voltage excitation, with a superimposed AC ripple. Experimentally, it is found that ripple amplitude and frequency strongly affect the development and pattern of PDs. These results should encourage researchers to assess ripple effects over the possible inception of PDs in DC cable insulation, reducing its expected lifetime.

Regarding threats to continuous operations of HVDC cable connections, the propagation of lightning impulse to substations terminals may cause overvoltages significantly larger than the rated voltage of the system (depending on the attachment point and on the struck conductor). Ref. [18] deals with the effects of the propagation of lightning overvoltages in a multiterminal HVDC test grid, suggesting the coordinated installation of surge arresters to prevent failures.

Joints are recognized as typical weak points in cable systems. The authors of [19] discuss the DC applications of field grading materials (FGMs), displaying marked nonlinear conductivity (depending on the electric field intensity and temperature). FGMs are to be designed, as to their base conductivity in the linear region and switching electric field, to limit the electric field strength at the insulation interface while containing conduction losses. The electric field distribution in non-stationary conditions should also be considered, especially for application in LCC systems. In [20], the tangential field distribution at the interface between the cable insulation (XLPE) and different joint materials is investigated, showing that the materials' mismatch has an impact on the computed electric field at different sections of the joint.

Finally, limitations derived from electro-thermal stress at a system level lead to considerations in [21] with respect to the insulation of a ±200 kV converter valve unit in a HVDC valve hall. The analysis, performed by means of the finite element method, assesses the air clearance between the converter valves and wall and ceilings and the minimum flashover distance of the insulators. Moreover, a DC corona shield is designed. In [22], the operation conditions of the hybrid DC breaker proposed by a major manufacturer [23] are evaluated; light is cast on the energy absorption by the metal oxide surge arresters (MOSA), during the interruption of different values of fault current, and on the electrical and thermal stress on the IGBT valve. In [24], an online failure diagnostic test for the full-bridge module used in an MMC is proposed. A short-circuit current diagnostic topology based on an integrated circuit is presented, and its performances in response to common IGBT power module failure mechanisms are analyzed.

Against this background, the authors of [25] suggest an iterative procedure to improve the accuracy in the calculation of RMS values of short-circuit currents, including the effective contribution of VSCs, in both cases of symmetrical and unsymmetrical faults and for various VSC control strategies. The proposed procedure is validated through comparisons of the derived results with those obtained using commercial software.

Strong interest surrounds the implementation of converter control strategies to strengthen the role of DC connections in the improvement of network stability, voltage balancing, inertial support [26], harmonic distortion, and so forth.

The authors of [27] introduce an improved Lyapunov-based stability analysis for power systems considering the probable widespread diffusion of modular multilevel converters in the near future. Compared to previous works, the analysis concerns a 12 bus test grid with multiple synchronous generators and converters connected in Grid-Forming Mode, also considering several possible converter control strategies.

Ref. [28] discusses an innovative Voltage Balancing algorithm for the control of the voltage of MMC submodules. The computations are performed directly by the submodules' electronic driver, relieving the main control unit of the associated computational burden.

A control strategy for a MMC-based active filter for the harmonic compensation of nonlinear loads is proposed in [29]. The control strategy combines model-based predictive control, phase shift PWM modulation, and suboptimal DC link power control, simplifying the control system and decreasing the computational burden.

The authors of [30] have developed an improved algorithm, based on the Particle Swarm Optimization algorithm, for the dynamic tuning of control system settings of converters operating in a multiterminal HVDC grid. The algorithm tunes the proportional–integral gains of the inner control loops of the grid converters in real time, taking into account the operating point of the overall system, enhancing steady-state and transient performance.

Acknowledging the spread of offshore windfarms adopting industrial converter control systems available in the market, a frequency-sweep black box approach is discussed in [31] to overcome the difficulties linked to the limited information regarding these control systems. The scope of the work is to derive a mathematical model suitable for stability studies, the parameters of which may be derived independently from different entities (e.g., manufacturers and transmission system operators) and shared without prior harmonization.

As for the transient performance of grounding systems, the following recent studies can be mentioned. In [32], the authors propose a simplified numerical model for overhead line ground electrodes based on the finite-difference time-domain (FDTD) method. The model is based on the spatial discretization of ground electrodes, and it takes into account the soil ionization phenomenon. The results are shown to be in accordance with previous publications.

Ref. [33] focuses on the soil ionization phenomenon. Many experimental tests are used to assess the effect of soil ionization on the grounding conductor response to lightning current dispersion for soil resistivities spanning from approximately 0.1 kΩm to 10 kΩm. An empirical curve relating the equivalent grounding conductor radius to the dispersed current is proposed.

In [34], the FDTD method is used to define a model for the evaluation of the lightning performance of grounding electrodes. The proposed model, applying absorbing boundary conditions, implements a dedicated methodology which considers the frequency dependence of soil parameters by means of the modeling of Debye medium through an auxiliary differential equation. The results provided by the FDTD method are compared to those provided by simulations based on the Hybrid Electromagnetic Model.

In [35], the authors analyze the lightning performance of overhead distribution lines located in high-resistivity soil. Several simulations are performed based on two case studies, and results are discussed regarding line protection from direct and indirect lightning strikes. An alternative solution for the protection of the line against direct lightning strikes is proposed to reduce surge arresters' failures.

The authors of [36] investigate the effects of soil structure on the ground potential rise in substation areas following switching/lightning transients. The analysis is carried out by means of the Method of Moments (MoM), and the frequency dependence of soil parameters is included in the calculation of the peak transient overvoltages; moreover, both uniform soil and two-layered soil are considered.

A detailed lightning surge analysis of an offshore windfarm is performed in [37]. After the comprehensive mathematical modeling of the wind turbines, the offshore platform, and the transmission system, a series of simulations are performed by considering three scenarios, i.e., lightning striking on the turbine blade, on the offshore platform, and on the onshore overhead transmission line. For each case study, the overvoltages at critical nodes of the system are evaluated. Finally, the authors discuss the influence of the submarine cable length on the transient overvoltages.

An alternative calculation procedure for the transient overvoltages following the energization of a cable line is proposed in [38]. The transient voltage profile is deduced as a function of position along the entire cable length: first, modal transformation is used to diagonalize the impedance matrix; then, the Laplace transform is applied to each independent mode to give the modal voltage profile. Finally, the transient overvoltage along the cable is provided by the numerical inverse Laplace transform and modal-phase transformation. The results are benchmarked with those provided by the frequency-dependent phase model used by the commercial software PSCAD.

The choice of specific modeling approaches for grounding systems is relevant when analyzing transients involving the propagation of overvoltages along HV and distribution lines. The authors of [39] compute the backflashover performance of a 400 kV transmission line in Denmark equipped with composite pylons and discuss the impact of different values of grounding resistance and soil resistivity; a simplified equivalent circuit of the grounding down-leads is adopted. Additionally, the technical practice of partial grounding is discussed with regard to the influence of maximum and minimum distances of the nearest grounded poles to the striking point along the line on the backflashover rate.

In [40], a simplified model for the calculation of the transient overvoltages in radial MV distribution networks is proposed. Using readily available distribution system data, an equivalent, lumped-parameter, single-phase circuit based on Clarke transform is set up, and system overvoltages following line-to-ground fault are simulated. The results are in good agreement with those provided by the three-phase distributed-parameter model, and a drastic reduction in the computation time is achieved, making the algorithm suitable for large-scale parametric studies.

The chain matrix theory is exploited in [41] to assess overvoltage mitigation by means of additional ground wires along distribution lines. The proposed method in the frequency domain allows frequency-dependent soil properties, grounding impedances, and tower modeling to be accounted for, provided the line structure is periodic (e.g., equal spans and constant grounding impedance along the line).

A new current differential protection scheme suitable for active medium voltage distribution systems is introduced in [42]. The main contribution of the proposed scheme is in the minimization of the network area disconnected in the case of a fault, implementing multiple differential elements to each differential protection zone. Special logic is defined to avoid tripping during external faults caused by distributed generation infeed. The applicability of the protection system is demonstrated in a real distribution system operated in a closed ring.

It is known that distance protections commonly used in transmission systems may not operate reliably in the presence of a high share of distributed generation, especially when the fault resistance is not negligible; this is compounded in the case of asymmetrical faults by the inverter response which may differ greatly, depending on the inverter manufacturer and model. Analytical correction factors are proposed in [43] for the ground- and phase-distance algorithms, considering whether the inverter is supplying negative sequence current.

The protection of closed-ring distribution systems with distributed generation is dealt with in [44]. An algorithm, based on the measurement of negative sequence currents contributed by the feeders at the busbar of a ring distribution network, allows the fault to be located in one of the two branches of the ring, associated with the choice of a ring breakpoint, or reference node, with peculiar electrical characteristics. The measurement of the voltage is not required, since the method relies on the comparison of the negative sequence currents associated with the relays installed at the two feeders, or on threshold values and logic conditions set preliminarily, according to the network topology and negative sequence impedances along the branches. The algorithm is not affected by distributed generation presence and/or fault resistance. The faulty branch can be readily located, and a selective opening can be operated.

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