Numerical Simulation of Compressible Magnetohydrodynamic Plasma Flow in a Curcuit Breaker

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The main function of a circuit breaker is to switch off the electric current safely, in case of fault current. During the switching off many processes take place. When a fault current occurs, a mechanical force separates the contacts, and an arc starts to burn between the two contacts, due to the current flowing from the electrodes. This high-temperature arc dissipates large amount of energy. Simultaneously this energy has to be transfered away from the contacts in order to protect the components of the circuit breaker. In order to interrupt the current, the arc must be weakened and finally extinguished.

Plasma in the arc consists of electrons, neutrons, ions and photons. It is electrically neutral. Compared to an ordinary gas plasmas are electrically conductive due to the presence of free charge particles. In fact, in many cases the conductivity of plasmas can be higher than that of metals at room temperature. Due to this property, plasma flows are very interesting to study because it involves both fluid dynamics properties and electric properties. In addition fluid dynamics properties influence electric properties and vice-versa.

In order to study the arc behavior in the chamber of the circuit breaker and effects of external magnetic fields on that, several theoretical approaches can be considered. Generally, these approaches do not exactly model all the phenomena in the arcing chamber and switching process. This is due to the complicated three dimensional geometry and involvement of various physical effects (like strong variation of conductivity of the gas) which make the computation of these model highly expensive. Also all the physical parameters(e.g. viscocity, electric conductivity, thermal conductivity etc.) depends on the gas. Normally in circuit breakers sulfur hexafluoride (SF_6) is used due to its much higher dielectric strength compare to air. This property make circuit breakers more suitable for indoor placement, compare to the air based circuit breaker which takes considerable more space.

A usual approach to model plasma flow in a circuit breaker consists of simulating the hydrodynamics part consisting of the compressible Navier-Stoke's equation, coupled with electromagnetic part consisting the Maxwell's equations. These equations are then coupled by modifying the momentum conservation equation by adding the Lorentz's force term into it. The energy equation is modified by adding the Joule heating term and considering the radiation losses. From the hydrodynamics part temperature is calculated which is used to provide the conductivity profile of the gas used in simulating the Maxwell's equations. This coupling is called a *weakly coupled* system. This model works well when conductivity is relatively low.

A true description of plasma motion must rely on kinetic equations for each plasma species. As this approach is too costly to simulate, a fluid description of the plasma is often used. This description is obtained by taking velocity moments of the kinetic equations describing a plasma under certain closure assumptions, and assumptions of high collision frequency. The equations of Magnetohydrodynamics (MHD) gives a single fluid description of a plasma in which a single velocity and pressure describe both the electrons and ions. At very high currents (10kA-200kA), in the vicinity of the arc high temperature produced by fault current are expected. As a result one will have a high conductivity. This implies strong coupling between hydrodynamics part and electric part of the model. Due to this a *strongly coupled* model based on the equation of resistive magnetohydrodynamics is adopted in this work. This model is suitable for the simulation of the plasma flow with relatively high conductivity. These equations are modified to incorporate the radiation effect, by adding Stefan's radiation term in total energy equations.

To simulate the plasma in the arc the Nektar code developed by Brown University is used in this work. This code is based on the Discontinuous Galerkin(DG) methods. It can solve the equations of fluid dynamics as well as the ideal and real MHD equations on unstructured triangular or quadrilateral meshes in two dimension and hexagonal or tetrahedral meshes in three dimensions. GID is used for mesh generation in both 2d and 3d. In the present work this code is

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extended to include Runge-Kutta time stepping, various accurate Riemann solvers for MHD, slope limiters and SF_6 gas data. It operates on both serial and parallel computers with arbitrary number of processors which is then ported to the large computing cluster. It is first used to investigate the suitability of Runge-Kutta Discontinuous Galerkin (RKDG) methods. The role of the numerical flux calculator in RKDG methods is addressed too.

The spectral properties of RKDG methods are investigated by computing their approximate modified wavenumber behavior and by comparing numerically obtained spectra to that of an exact solution. The modified wavenumber behavior of high-order unlimited RKDG scheme is found to be excellent. In particular, the dispersive performance of the fourth-order scheme is remarkably good. The dissipation of this scheme is very low, even at highest wavenumbers. When limiting is required, however, the spectral performance of RKDG schemes tends to that of the first-order method at high wavenumbers. Hence in the vicinity of discontinuities, high-order RKDG methods exhibit high numerical dissipation due to the use of limiters which reduce the polynomial order of the approximate solution to at most one.

To investigate the importance of accurate Riemann solvers in RKDG simulations, the results of first-,second-,third- and fourth-order simulations of both smooth and non-smoth problems are examined, along with the approximate wavenumber behavior. For smooth solutions we find that the use of accurate Riemann solvers significantly improve the imaginary modified wavenumber behavior of RKDG methods at high wavenumbers, indicating that numerical dissipation of high wavenumber modes is reduced. For second- and third-order schemes, the behavior is confirmed by comparing the spectra from numerical solutions to that of the exact solutions. However for the fourth-order scheme, the Riemann solver used has negligible influence on the numerical solution.

It is found that for solutions dominated by discontinuities, high order RKDG methods behave in a similar manner to the second-order method due to use of a piecewise linear limiter. Thus for such solutions, the choice of the Riemann solver in a high-order method has similar significance as for the second-order method. Our analysis of second-order methods confirms that the choice of Riemann solvers is very significant. The more accurate Riemann solvers required to have lowest computational effort to obtain a given accuracy.

To simulate a plasma arc based resistive MHD using RKDG methods we first have to generate the *numerical arc*. For this purpose one assumes that there is an initial arc with the given current 100kA and applies suitable boundary conditions depending on the incoming fault current 100kA. This initial arc is simulated until the steady state is reached. This is considered to be the *numerical arc*. To study the effects of external magnetic fields on the arc one applies the same conditions but adds external fields into the system and modifies the corresponding boundary conditions. It is shown that it is possible to generate a rotating arc with the external magnetic field. This produces a pressure build up which will extinguish the arc. This work has been performed by Patrick Huguenot and Harish Kumar in their Ph.D. thesis and by Vincent Wheatley.