

Combining Textbook Material And Current Research In A Graduate Course In Energy Systems

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Abstract

Conventional graduate courses in electrical power systems generally offer diversity into specific areas of energy and power systems such as transient analysis, power electronics, and high voltage DC (HVDC) systems. An energy systems course in the Electrical Engineering Department at Texas A&M University has been redesigned to incorporate a new approach which promotes a creative environment to think beyond the barriers of traditional technology. By applying the basics and history of power transmission, students are encouraged to study architectures of conventional and unconventional energy systems. Open group discussion and free-thinking are combined to explore new concepts and domains of energy systems. Some of the specific new power system concepts that are discussed in the course are presented in the paper in an organized way.

Introduction

Undergraduate courses in conventional electric power systems are well established at most engineering universities. Graduate courses offer diversity into particular areas of energy and power systems, such as transient analysis, power electronics, and high voltage DC (HVDC) systems. However, in the Electrical Engineering Department at Texas A&M University, an energy systems course has been redesigned to incorporate a new approach which promotes a creative environment to think beyond the barriers of traditional technology. By applying the basics and history of power transmission, students are encouraged to study architectures of conventional and unconventional energy systems. Open group discussion and free-thinking are combined to explore new concepts and domains of energy systems. This provides the students with the opportunity to explore, organize and possibly contribute to existing research results at Texas A&M, on new energy system concepts.

This graduate course in the Electrical Engineering Department at Texas A&M was originally instructed by the professor in 1983, and is presently entitled "HVDC and Other Unconventional Power Systems." The principal purpose of the course is to explore the concept of electric

power and energy systems in their most general form. To accomplish this, the semester starts with one of the more familiar unconventional power transmission systems: HVDC transmission. The professor uses this subject as an introduction to the idea that there are other means of transmitting power than conventional AC lines. Textbooks and current research materials are then used by the professor to develop new energy system concepts. This study provides students with a historical perspective on how and why the conventional power systems turned out to be the way they are today. More importantly, the course shows that power and energy systems can be conceived and designed on totally different bases. Exploration of alternative power and energy system architectures is encouraged by the instructor. The course material also shows that what determines the appropriate power or energy system is the state of component technologies at the time, and the particular system application architecture. For example, energy system architectures in various terrestrial, air-borne, or space applications are distinct because of different design constraints. Furthermore, superconductors can theoretically provide radically different system architectures with superior performance and flexibility.

Although the technical level of the course topics requires basic understanding of conventional power electronics and power systems, a great deal of new thinking and self-study is involved.

This paper describes the instructor's approach to this course and briefly outlines the contents of the course topics. Some of the specific new power system concepts that are discussed in the course are also presented.

Course Objective

The objective of this course is three-fold. It begins by acquainting the students acquainted with the historical progression of technological developments that have led up to energy systems in existence today. Having laid this foundation, the course proceeds to the second stage, which requires students to research into published literature on alternative technologies and architectures that have been investigated but not yet implemented due to practical

constraints. The third stage comprises investigating these constraints to explore possibilities of surmounting or circumventing the technical difficulties which obstruct the implementation of newly conceived technology. In so doing, the students participate in “free-thinking” to explore new avenues without being encumbered by the consideration of traditional technological constraints. This approach opens up the interesting possibility that the students may actually conceive a new application or architecture.

The course content begins with an overview of the development of power system architectures from the times of Edison, through the developments by Westinghouse, up to the form in which they exist today. While this is reviewed independently by the students, the instructor concurrently covers HVDC transmission to comprise the first phase of the course. The second stage builds on this historical foundation by exploring non-traditional concepts such as the Flexible AC Transmission Systems (FACTS), which has been investigated but not yet implemented. The completion of this exploration and subsequent discussions opens the doors to the final phase of the course, the content of which is entirely unknown and undefined. This is precisely the objective of this phase: to speculate and conjecture into the realm of the future.

Course Structure

Conventional power transmission systems are generally automatically assumed to be high voltage AC (HVAC) transmission. Using a prerequisite understanding of conventional AC transmission, emphasis on alternative power systems introduces students to advancements in technology and concepts beyond conventional assumptions. High voltage direct current (HVDC) transmission, perhaps the most well known power system variant, serves as an introduction to the course.

The structure of the course can be considered as a hybrid between traditional teaching and student participation. Course materials include a text book on HVDC and numerous articles relating to HVDC, electromagnetic energy storage, flexible AC transmission systems, and superconductive power systems. The lecture is conducted in a seminar-like fashion, where the instructor presents segments of information followed by questions and discussions. Since some of the subjects are very recent and sometimes inconclusive, occasional unresolved questions are assigned as ‘homework’ and further discussed in later lectures.

Since part of the intention is to promote critical inquiry, the students are encouraged to look beyond the obvious and probe the evolution of existing energy systems. Groups of students are assigned to study the historical progression of power system architectures. Detailed analysis pertaining to the various elements constituting the table of power system architectures (Table I) will be discussed in the following sections of the paper.

The Historical Progression Of Power And Energy Systems

Introduction

Electricity was a major invention for mankind, for without it today, life would surely be completely different. The delivery of electricity and the historical progression of energy systems has taken an interesting path, especially before the turn of the twentieth century. Of the inventions and developments over the last century, electricity and power systems have played an extremely important role in society. “The half-century from 1880 to 1930 constituted the formative years of the history of electric supply systems” [1].

DC systems were the first to be implemented by Thomas Edison in New York during 1878. DC systems were probably a logical choice due to the availability of storage batteries at the time. Efficiency and economy were the main constraints for system design and operation.

During the first decades of power generation, reciprocating steam engines and steam and water turbines were predominant, coupled to various types of generators. Before the end of the nineteenth century, the invention of the AC transformer and the induction motor made AC power transmission more practicable. Transformers became the principal means of transmitting and distributing power and the distance of power transmissions increased.

The First DC Electric Supply Systems and Distribution Difficulties

The dawn of the electric age was heralded in September of 1882, with Thomas Edison’s Pearl Street generating station which was a direct-current, 2-wire electric supply to a few hundred light bulbs in downtown Manhattan. In the same year, Marcel Deprez demonstrated the first transmission of HVDC power in Germany where 1.5 kW was transmitted at 2.0 kV over a distance of 57 km [2,3].

Improvements were made in the 1880s on slow-speed DC generators, increased generator capacities, and effective generator control. In addition, DC motors were developed for various loads to compete against steam and gas engines. While great inventors and engineers had made these improvements in generators, motors, and other components of the direct-current system, there was still the problem of the high cost of distributing the power. Long distances posed especially high costs, which at that time a distance extending more than one mile was difficult [4]. Since the voltage at which DC power could be transmitted was limited by the generator and insulation technology at the time, the distribution costs of DC power were of the same order as that of production. Storage batteries were used with these DC distribution systems in an attempt to alleviate the transmission and distribution difficulties, but battery technology at the time could not surmount operating and maintenance difficulties. DC current transformation was also expensive with the use of inefficient motor-generator sets.

In response to the constraint of DC transmission costs, the three-wire distribution system was patented and introduced by Edison in 1883. This three-wire system saved 60% of the copper needed to operate the two-wire

network introduced with the Pearl Street generating station, and continues to be used for distribution systems today. John Hopkins from Britain, and Wilhem von Siemens from Germany had also applied for a three-wire distribution patent at the same time as Edison. Despite this improvement in the distribution systems, the cost and efficiency of DC distribution was still a major problem, especially in less densely populated areas.

The 'Battle of the Systems'

Frenchman Lucien Gaulard and his British partner John Gibbs were the first inventors to introduce the concept of alternating current systems with the use of open-core, variable voltage transformers to transmit and distribute electricity in 1883. This facilitated the use of AC, a more economical method to transmit power at high voltage over longer distances compared to DC at that time. Newer and more efficient transformers allowed for safe and usable low voltage AC power end delivery. The AC system and transformer design was later improved in 1885, by Bláthy, Déri and Zipernowski from the Ganz and Company in Hungary by the use of a closed-core and parallel primary coil connected version.

Even though engineers had greatly improved the DC system, the cost of transmission still remained a problem. Cost restricted the size of the (copper) conductor, thus limiting the expanse of the customer service area. The technology to increase and decrease DC voltage did not exist in the earliest days of the electric industry, so Edison had to transmit DC power at a relatively high current. The AC networks allowed power to be delivered at a relatively low cost to diverse loads from a number of large interconnected generating stations by means of integrated networks. However, the main drawback of the AC system was that there was no practical motor available, thus AC was only suitable for lighting loads. Another problem with the use of higher voltages in the AC systems was the need for better insulation. In addition, the problem of voltage regulation produced significant difficulties for acceptable operation.

Since AC power could be transmitted over longer distances, a single large central generation station was more economical than the numerous, small DC plants required for an equivalent effective system. Economical transmission also made production of AC more competitive since generating plants could be located closer to the fuel resources, which invariably saved more on land prices since these areas were mainly out of city limits.

In the years that followed, George Westinghouse and his engineers in Pittsburgh had contributed significantly to the development of the AC transformer components for economical and quantity production.

The first commercial AC lighting system was installed by the Westinghouse Electric Company in Buffalo, New York in 1886. Suitability of the AC system for transmission was strengthened with three technical developments in the following years of 1887 and 1888 [5]. Such inventors as Galileo Ferraris, Michael Dolivo-Dobrowolsky, Charles Brown, Friedrich Haselwander, and the Westinghouse

engineers were associated with the introduction of the AC motor throughout the world, but Nikola Tesla is recognized for first patenting the AC polyphase motor in the U.S. in May 1888. This motor allowed more load types to be served on AC systems apart from only lighting. The invention of the rotary converter allowed AC to be converted into DC for the supply of the already well established DC loads from the advent of the Edison system. This allowed various systems, including AC and DC, to be coupled with new ones. In addition, the development of an electric watt-hour meter permitted the monitoring of alternating current power usage, which enabled the fair pricing of electricity and the confidence in accurate billing of customers.

Due to the relative ease with which the voltage could be transformed, AC systems spread rapidly from that point forward in Hungary by the Ganz and Company, in Britain by Sebastian Ferranti, and in the U.S. by William Stanley. Contemporaries referred to the AC concept as a 'new system', and called the competition between the DC and AC supply of electricity as the 'battle of the currents', or the 'battle of the systems' [6].

All of the comprehensive electric power systems in operation in 1889, were DC. At that time, AC systems were only single-phase and were used exclusively for lighting loads [7]. A shortcoming of the single-phase AC system was that it could not operate self-starting motors. It was not until 1900, that the three-phase system was common.

The first successful high voltage AC power transmission system was demonstrated in 1891, with a three-phase, 175 km line from Lauffen to Frankfurt in Germany operating at 25 kV. This was also a successful demonstration of 'point-to-point' transmission from remotely located generation resources. At this time, oil was emerging as a practical insulating medium, especially for transformers. The selection of a 'universal' AC system by Westinghouse for the 1893 World Fair in Chicago, and for the huge hydroelectric generation and high-voltage transmission line installation at Niagara Falls the same year reinforced the impetus of AC power as a successor to the DC system founded only a decade earlier. The 'battle of the systems' was effectively ended in 1893. Some AC system architectures were standardized because of precedence and prior successful practice and not necessarily because of a clear technical superiority of one system over another.

The advent of the steam turbine which was more compatible with AC generation than low-speed water turbines, reinforced the availability and existence of AC power systems in the early 1900s. There were no specific disadvantages of low-speed water turbines for DC generation, but the use of steam turbines necessitated high-speed reduction gearing [2].

However, the transition to AC was not abrupt, and DC was still used for particular loads such as series arc lighting and railcars. By 1922, AC constituted 98% of total generating capacity in central stations [8]. The persistence of the DC traction load in the early twentieth century delayed the complete dominance of AC until 1982.

Hewitt's mercury-vapor rectifier which appeared in 1901 and the introduction of grid control in 1928 provided the basis for controlled rectification of AC and inversion of DC voltages [2]. Although the economic advantage of DC power transmission was still very much debated then (as it still is now), its practical application had to wait for the development of a suitable solid-state device with high voltage and current ratings. The first HVDC link, the Pacific Intertie, was implemented in 1954 and used mercury-arc rectifiers. DC power was, and still is, used to some extent in traction applications.

Origin Of The System Operating Modes

There were several types of generators employed in the DC and AC electric systems in the twentieth century [9]: DC constant current for series arc lighting, DC constant voltage (two-wire, three-wire, and five-wire systems) for lighting and motor loads, single and polyphase AC constant current for series arc lighting, and constant voltage with transformers for lighting, motors and DC loads.

From the early calculations made by Edison in designing his generating station on Pearl Street and with the advent of the AC systems in the 1890s which improved transmission and distribution at higher voltages, the need to reduce the conductivity arose as a major issue. More efficient conductors would benefit economically and improve voltage regulation and reduce ohmic losses in the system. Thomas Edison used a 'voltage source' system for his Pearl Street installation, and a 'voltage intensive' operating mode to reduce ohmic losses as much as the DC generator output voltage ratings would allow at the time.

Gaulard and Gibbs had adopted the constant current AC generator designed for arc lights connected in series for their first integrated AC system using transformers. With this 'current source' mode of operation, they had expected a constant secondary voltage on the transformers with the transformer primaries connected in series. However, if the load on the transformer secondaries varied, so did the secondary voltage, and Gaulard and Gibbs had to resort to complicated secondary circuit voltage regulators.

The Ganz and Company had greatly simplified the AC system design of Gaulard and Gibbs by introducing the concept of 'voltage source, voltage intensive' (VSVI) systems with the use of a constant voltage generator ('voltage source') and transformers with the primaries connected in parallel to step-up the voltage ('voltage intensive') for long distance transmission. This provided the basis for the 'voltage source, voltage intensive' systems still in use for conventional power systems today.

During the early days of AC and polyphase systems, designers and engineers chose the frequency that was optimum for the particular characteristics of the generators, transformers and different load types. The slower, directly-coupled generator was found by the Westinghouse engineers to be less complex when designed for lower frequencies, such as 60 Hz, since fewer field pole pairs were required. With the introduction of the high-speed generator turbine, even fewer poles were required than with the slower prime movers. The relatively lower frequencies were also well

suited to power transmission due to the line frequency-dependent characteristics. In the 1900s, 60 Hz was first established as a standard in the U.S. with 50 Hz as a standard in Germany. Only after the first world war was 50 Hz established as a standard in Britain.

The conventional power systems in use today are 'voltage intensive' with a given level of power transmitted and delivered with as high a value of voltage as can be reasonably achieved. Thus the current in the system is limited to a minimal level to render the intended power. For example, in bulk power transmission, the system voltage level is of the order of 345 kV, while the current is in the region of 1 to 2 kA. The primary reason for this 'voltage intensive' approach appears to be that efficient, low-loss voltage insulators are easier and more economical to achieve than current conductors [10,11]. In other words, by stressing the system voltage, the system does not suffer large insulation leakage currents which can lead to large losses associated with the voltage level. By comparison, today's poor current conductors produce significant ohmic voltage drops which cause large power losses associated with the current level. Therefore, power transmission is more efficient in the 'voltage intensive' mode at the present time since the existing voltage insulation technology is more advanced than the current conduction technology.

However, the above argument does not explain why the conventional power systems of today are voltage regulated or 'voltage source' systems. One of the most fundamental reasons why 'voltage intensive' systems today are also 'voltage source' systems is the following. If a high voltage system was a 'current source' system, then the system current would be constant, or 'stiff.' Thus, all the load elements would have to be connected in series, and the system voltage would be dictated by the sum of the load impedances (the current magnitude being constant at all times). At a light or no load, the system voltage would be low, or near zero, and at high loads the system voltage would be very high. Therefore, the fundamental premise of voltage intensity could not be maintained. Furthermore, the system losses associated with the high magnitude of operating current would be high and constant from no load to full load operation on the system. This is in contradiction with the basic approach of minimizing the current flow in today's conductors, at the expense of maintaining a high voltage on near perfect insulators to minimize system operational losses.

The above argument implies that the incentive for building a 'voltage intensive' system, also applies to a 'voltage source' system. Ironically, a form of 'voltage intensive', 'current source' power system is in use today; namely, HVDC power transmission [2,12,13]. However, this situation is forced mainly by the operation of the HVDC converters. Furthermore, the otherwise superior efficiency of these systems more than compensates for the nominally constant losses at all load levels. In addition, almost all HVDC transmission systems are two-terminal (point-to-point) architectures between fairly constant sources and loads.

Exploration Of Alternative Energy System Architectures

Trends in Existing Power Systems

Magnitude and frequency of voltage and current can be selected in many different ways to transmit power. Table 1 shows a classification of power system architectures based on the nature of V-I sources and their relative magnitudes. V-I sizing depends on the available technology. Due to the availability of nearly perfect insulators for high voltage but not of perfect current conductors, present day AC power systems use a Voltage-Source, Voltage-Intensive architecture. These systems are presently interconnected and formed into "grids" which cover geographically large areas.

The latest developments in these conventional systems center around "Flexible AC Transmission Systems" or FACTS [16]. FACTS involves the use of advanced solid-state controllers with power electronic switching devices located at existing transmission lines or substations. Some examples of FACTS which are being researched and field tested are:

- (1) Thyristor controlled series capacitor - changes the line impedance and allows more power flow through the line.
- (2) Static Condenser - acts like a shunt compensator which can both supply and absorb lagging VARs to maintain the bus voltage.
- (3) Thyristor controlled phase angle regulator - controls power flow in parallel AC lines and prevents undesirable loop flows.

Since FACTS uses high-speed switching devices it has the capability to improve the transient stability of the AC system.

		V - I S I Z E					
		HIGH VOLTAGE		HIGH CURRENT		MODERATE V,I	
		AC	DC	AC	DC	AC	DC
		HVAC		V S C I			FIRST EL. POWER SYS.
SOURCE BEHAVIOR	STIFF						
	CURRENT SOURCE		HVDC	C S C I			
SOFT		ARTICULATE POWER SYSTEMS					

Table I. Power System Architectures.

HVDC Transmission

The other element of Table 1 which is in common use today is the High Voltage Direct Current transmission (HVDC). It is classified as a current source, voltage intensive system due to the nature of the interconnection between AC systems and HVDC links. On the AC side the system appears as a voltage source but on the DC side the converter appears as a current source; this is necessary for control of the power flow from the AC side to the DC side

or vice-versa. HVDC links have primarily been used for bulk power transmission over distances where AC lines or cables become uneconomical or technically constrained [17]. Because HVDC allows the interconnection of two AC systems which are not synchronized or have different frequencies e.g. 50Hz and 60Hz, it is used for back-to-back ties between two AC grids. Until now, the focus was on 2-terminal HVDC links. Recently work has been done on multiterminal DC schemes [18] and two such schemes are in operation:

- (1) Nelson River 4-terminal
- (2) Sardinia-Corsica-Italy 3-terminal

Basically these schemes involve parallel taps on the main 2-terminal DC link. The limitation is unavailability of DC circuit Breakers of sufficiently high ratings. Due to higher transmission efficiency and faster dynamic control HVDC systems continue to be developed. New advances can be applied to further stabilize the existing AC system.

Utilization of Superconductors

Intensive research being conducted on superconductors and room-temperature superconductors may become available in the near future. The availability of superconductors opens up the possibility of implementing a Current-Intensive system. Models of Current-Source, Current-Intensive systems have been actively researched at Texas A&M University [19]. Essentially a high current DC system combines the advantages of DC transmission with the unique features of superconductors. A simple topology is shown in Fig. 1, with DC converters connected in series and a single transmission line without ground return forming a closed loop for the current.

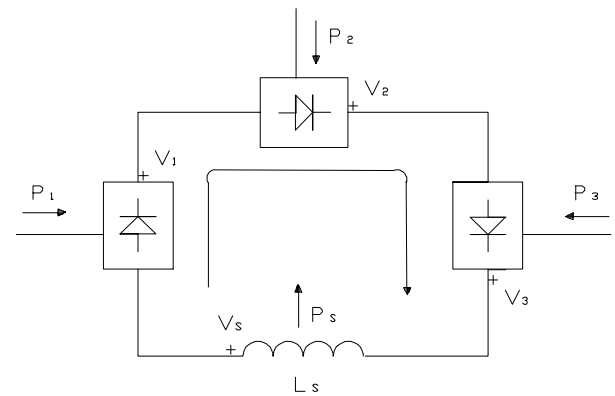


Fig. 1. CSCI power system architecture

P1 could be power input from an AC system or generation. Similarly P2 and P3 could be generation or loads on the AC side. The inductor L_s represents the distributed inductance of the entire loop which would be substantial for any practical transmission distances. Due to the high inductance the system naturally behaves as a current source. The superconductor not only eliminates conduction losses but the high DC current means that a large amount of energy is stored into the magnetic field surrounding the line. This energy can be used for load-leveling and riding through disturbances. Load-leveling

helps to reduce the size of generating units required. Some practical aspects are:

- (1) Faults would be open-circuits which have to be cleared by circuit makers (crowbars).
- (2) High magnetic fields around the lines can be hazardous to personnel and instruments.

This could be circumvented by magnetic shielding of the line by using two lines in a coaxial configuration, losing the use of stored energy in the magnetic field. Superconducting Magnetic Energy Storage (SMES)[20-22] units could be placed in the system at suitable locations to perform this function. They would consist of large superconducting coils acting as a substitute for L_s . Research and testing of prototype SMES units is under progress.

Missing elements of the Architecture Table

The remaining "missing" elements of Table 1 were examined. As observed in section 5.3, the current intensive system is more amenable to current source implementation rather than a voltage source concept, because the current is "stiff" due to high inductance of system.

The last entry in the table is the Articulate Power System. It is a new concept which allows flexible V-I sizing during operation to optimize the transmission of power. This AC system is operated such that $V/I = Z_0$ at all times, where Z_0 is the natural or surge impedance of the line. The concept of continuously naturally loaded transmission lines allows operation of lines at their thermal limits as the reactive power demand of line is zero. Thus neither V nor I is stiff but 'soft'. Also, the system frequency is varied to optimize generator operation. Then a frequency changer would supply the load with fixed frequency AC and stiff AC voltage. These are all theoretical concepts but could be implemented with existing technology of power electronic converters. In conclusion it is observed that although conventional AC systems are well established for terrestrial power systems, the alternative architectures are quite feasible for applications on ships, airborne and space platforms which have different power sources such as propulsion drives, solar cells, etc.

Conclusion

This paper presented the philosophy and organization of an energy systems course, offered at Texas A&M University, which was redesigned to promote a creative environment to think beyond the barriers of traditional technology. This paper described the manner in which conventional teaching techniques were integrated with group research efforts by the students. The organization of this course is a dynamic entity and will continue to adapt itself to keep up with technological advances in power systems and power electronic equipment.

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