Power Network Analysis

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Week - 01

Lecture - 01

Hello everyone, welcome to this NPTEL course on Power Network Analysis. This is the first lecture of this course in which we will discuss about the different topics to be covered as part of this course. As you can see, we will start with the basics of circuit principles followed by a discussion on transformers and the related per unit analysis followed by the discussion on the synchronous generators which are the main generating resources in the given network that we have power network that we have. And then we will take up few discussions on transmission line parameters and the related models. These transmission line parameters and the related model that we will discuss, they would help in understanding how the network behaves, how power is being transmitted from the synchronous generators to the different loads that we have. The loads could be categorized into industrial, residential and so on, which we'll also discuss in today's discussion.

having brief idea of all these important network elements then we will go into the three most important tools necessary for understanding how the power network works the first one of them would be power flow analysis which is a well-known steady-state tool followed by a discussion on how the network behaves during electrical faults wherein the next module on fault analysis would help in and lastly we would discuss on the aspect of certain algorithms or techniques how power network stability can be understood and analyzed. So if we look at the history of power networks, it's a relatively 150 years old history, wherein the first DC network was sort of set up by Thomas Alva Edison in 1882 to sort of supply power mostly for lightning loads in the lower Manhattan area of New York. The network initially sort of provided power to around 500 customers and the operating voltage which was initially 110 volt DC was later upgraded to 220 volt DC. Because of the DC structure or DC behavior of this power network, the power distribution was   limited   to   a   very   small   area.

because of the high I2R losses or copper losses that were being endured in the underground cables that were set up for sort of passing on the electrical power to these 11,000 bulbs. And unfortunately around 1895, the Pearl Street station where all these DC generators were

set up, it got caught fire and then was later decommissioned in 1895. Another reason why the DC network which was set up by Thomas Alva Edison probably lost its ethos or purpose of supplying electrical power was in the meantime, AC elements specifically transformers and induction motors, they had their concept, their idea had also come in thanks to William Stanley and Nikola Tesla. And around the same time, we also had our first single-phase AC network in Oregon City, where power was generated from two 300 horsepower hydro generators. And the transmission was done to an area in Portland at 4 kV, and the length was around 21 kilometers.

Again, this was a very small single-phase AC power network. Germany was in forefront of establishing the first three-phase AC network in 1891 with operating voltage around 12 kV. The operating frequency for AC networks, there was no standardization. All these networks, they were isolated networks. They were not interconnected.

And there was a lot of debate around that time. What should be the standard frequency of electrical power network? So a lot of work went on. A lot of discussion went on. And eventually, for USA and Canada, the standard Electrical frequency of power network is 60 Hz while the rest of the world is happy at 50 Hz now it was Interesting to understand why USA and Canada chose 60 Hz and why rest of the world electrical power network operates at 50 Hz. There is probably no conclusive technical answer to it.

Probably USA and Canada, they wanted to be a little different from other networks, other countries. So that's why they chose 60 Hz as their operating frequency. Again, Indian power network history is also very interesting. Thanks to the British administration, we had our first DC network in 1879 in Calcutta. And the first hydro pump or hydro installation, hydro plant was installed in 1896 by Crompton and Greaves.

Now it is known as Crompton and Greaves. Earlier it was Crompton and Co company with capacity of 130 kilowatts. The first thermal plant came up in 1899 of capacity of around 1 megawatt, thanks to Kolkata, Calcutta electricity supply company, which is still operational after so many years. And post-independence, we had our first electricity supply act that paved the way for modernization of Indian power network as a result of which several state electricity boards were formed who would regulate, monitor and operate their generation, transmission and distribution and central electricity authority was also commissioned to oversee the planning and operation of the entire Indian power network. The Electricity Supply Act had gone through several revisions, amendments I would say.

In 1975, the first significant amendment which came up was establishment of National Thermal Power Corporation, National Hydro Power Corporation and Nuclear Power Corporation of India Limited. These companies or these corporations, they are now all

Navaratnas or Maharatnas and in 1989, National Thermal Power Corporation NTPC was further segregated into two distinct bodies. The portion which was responsible for ownership of centrally owned thermal power plants, it retained with NTPC, but the transmission network was sort of supervised to Power Grid Controller of India Limited, which we know of as PGCIL. who was responsible for planning operation and maintenance of the transmission grid interconnecting different state boards. 2003, the Electricity Supply Act was further amendment and all these amendments were superseded by when compared to the previous changes that happened in.

As part of which CERC came into existence, Central Electricity Regulatory Commission, which is a regulatory body and is responsible for approving all policies and regulations that do come in from the operational installation and functioning perspective. And PGCIL was again segregated into two distinct government of India entities. One was PGCIL itself, which was operation for planning and maintenance of the transmission network, whereas the operation part was handed over to POSOCO, formerly known as POSOCO, which was Power System Operation Corporation Limited. Indian network power grid if we talk about it has five regional grids as can be seen in the figure here. The source for this figure has also been given in the link below.

1991 prior to that all these five regional grids, northern, northeastern, eastern, central and southern or western and southern, they were all independent, they were not interconnected. So basically Indian Power network was consisting of five sub networks. 1991 northeastern and the eastern grids which are these two grids, they were interconnected And subsequently in 2003 and 2006, the western grid and the northern grid were interconnected to these existing north eastern grid. And finally in 2013, the southern grid was interconnected to all the remaining four regional grids wherein we had our first one nation, one synchronous grid operating at 50 hz. By synchronous grid I would mean if we were to have 2 meters which could measure frequency at distinct parts of this Indian power network and we were to take a reading.

or record of what frequency is, we would eventually have the same frequency reading at a given point of time, even if it is to be measured at different locations, let us say a meter placed in Gujarat somewhere or a meter placed somewhere in Assam, they would both show 50 Hz as or whatever the common synchronous frequency, they would both provide the same reading. Typical voltage levels in India, the generation is typically around 11 kV, 20 kV, three phase again, line to line. And transmission, the operational perspective, the highest operating voltage in transmission is 765 kV. Although plans are already in place where the 765 kV may be upgraded to 1100 kV. In addition to these AC voltages we also have high voltage DC network which again serves as a good backbone for transmitting power from generating stations to the loads.

Typical sub-transmission or distribution is at 33 kV or 11 kV and finally this power which is generated at few 20 kV or 30 kVs get transmitted through these different voltage levels and finally the consumer like us we consume power at 415 volt three phase or 230 volt single phase typically all these voltages which have been mentioned here they are essentially three phase line to line voltages we will discuss about these three phase line to line voltages probably in the from the next lecture onwards And government of India has also put in ambitious target of having 500 gigawatt of renewable energy integration by 2030. So far, we are in 2025. So, so far, almost 20% of this target has already been achieved. And it is quite hopeful that we'll be able to reach up the remaining 400 gigawatt, close to 400 gigawatt integration eventually by 2030. If you look at the statistics of how much is the installed generation capacity in India, then we are close to 466 gigawatts, basically, out of which around 56% or 57% was the share by thermal power plants.

Now, these thermal power plants, they are coal-based, lignite-based, gas-based, and diesel-based. The relative percentages are also given here. The numbers that you see in black, they refer to the previous year's data. By the way, these data points are well maintained at CEA website, the link of which is given here. So any enthusiastic can keep track of how these numbers evolve over time by referring to this particular link.

So the numbers that we see in red, they are the numbers as of January 31st, 2025, whereas the numbers which are given in black refer to the number as per May 31st, 2023. And over the years the percentages they have evolved as you can see. The most significant change which is appreciable enough is the share of renewable energy resources which has gone up from 30% to almost 35.5% within two years. And if we look at the share of these installed generation capacities which are owned by states, central sectors and private sectors over the years, the percentage of private entities have also gone up in generation perspective.

Almost two years back in 2030, this number of private sector was close to 50% and it is eventually growing, we are now close to 54%. The targeted thermal plant load factor for 2025 as set by CEA is 70% and ideally speaking if this plant load factor reaches 100% that would be the best possible situation for the entire power network. What is this plant load factor? We will talk about it in the next few slides to come. Talking about smart grid, the network, the conventional power network, it has gone through several transformations. So the figure that is now as of shown here, it typically represents the conventional vertically integrated network wherein power was always fed from the generating stations to the transmission network, then from there it used to come to the distribution network and from there the industrial commercial and residential loads used to get their share of power.

Over the years specifically in the last two to three decades this flow or unidirectional flow

of electrical power has substantially changed, the reason why it has changed thanks to lot of renewable integration which has been happening both at the distribution level as well as transmission level as long as more and more renewable integration is being presented in the distribution and transmission level there would obviously come a situation where at some point of time a given electrical network may have excess of power and basic energy conservation states that energy once created cannot be destroyed or it cannot be created it basically it can only be transferred from one mode to the another same goes with power it cannot be created or cannot be destroyed its transformation can only happen so in a situation where a network thanks to lots forward from one mode to the another same goes with power it cannot be created or cannot be destroyed its transformation can only happen so in a situation where a network thanks to a lot of renewable integration has excess of power at a given point of time that power has to go somewhere so basically these blue colored single arrows they are now becoming bi-directional arrows where a given point of time both ways power can be transferred and all these entities they are also communicating with each other through the intelligent communication network, ICD network. So all these bidirectional flows of power, communication capabilities, etc., etc., has made the network more flexible, more controllable, and more secured in a way that if one entity is like, let's say, a residential load is facing power crunch, So that residential entity probably can communicate with the nearby load or nearby roof of solar power and request for more power procurement in a way possible so that the power crunch can be alleviated. So that's how the power network has become more smart.

That's the essence of the notion behind the smartness. Smartness is all about additional flexibility, additional controllability and additional security thanks to bi-directional flows of power and communication infrastructure that is there. Some of the few trending concerns which exist in current times are lot of push has been given to integration of renewable energy resources into the existing power network but these renewable energy resources they are highly uncertain and variable because their generation is heavily dependent on the weather. So for solar PVs, it is mostly solar irradiation which is available while as for wind, it's the availability of wind. And we'll talk about this inertia and stability aspect in the last module.

Because of high renewable energy integration, the existing system inertia is being reduced because solar PV panels, they are mostly non-rotating devices. So as long as more and more stationary devices or non-rotating generation is being penetrated into the network, the overall system inertia is being reduced and there might be stability issues. We as of now don't have any standard operating procedure for handling EVs in the sense how EVs are to be modelled electrically, how their charging and discharging technology is to be adapted for the Indian network that is still missing. We are also probably facing issues from the upgradation of existing power network in terms of its operation, protection and control.

active distribution networks they are now bi-directional so controllability becomes a challenge specifically for the substation or distribution level transformers which were originally designed to have a single directional flow of power we don't have typical or standard operating procedure for distribution system operators in short known as DSOs and how these different DSOs would interact with the transmission system operator who basically operates the networks.

 So basically it's POSCO or grid controller of India. So how would POSCO interact with the operator at POSCO interact with the operator of distribution network? Those interactions, those procedures are still not matured yet. And lastly, the loads, they still lack participation from demand response perspective. It's pretty evident now that with the demand response actions coming in, the systems or networks flexibility enhances significantly. We have to sort of think about how loads can participate more effectively from both cost and economics perspective.

 And can our renewable energy resources also provide ancillary services like the existing conventional generations the way they are? So all these are some of the few trends or few concerns which need some understanding, some research to address those challenges. Coming at the system operation perspective, it's pretty evident that the electrical power network that we have, it's one of the most complex man-made networks with lot of interconnections in which we can categorize this network into four distinct entities, the first being generation, Second being transmission, third being distribution and finally the loads. All these entities which we have figured out or talked about, they are owned, operated and controlled by several entities. So if we talk about the Indian perspective, we have lot of state owned, centrally owned and privately owned generation utilities. Same thing also goes for the distribution network.

 There are different state-owned as well as private-owned DISCOMs. The interesting part is so far there has been no private player directly involved in the Indian transmission level. it is still being owned and operated by posoco which was till 2025 known as 2022 known as posoco and later on posoco has been re-ventured or renamed as grid controller of india limited basically in short known as grid india or gcil grid controller of india limited There are five RLDCs, one each for each of those five regional power networks and one National Load Dispatch Centre which is owned by Grid Controller of India Limited. We also have two power exchanges, Indian Energy Exchange and Power Energy Exchange India Limited which were set up in 2008 wherein different private players and state-owned utilities at generation level or at distribution level, they can bid energy and buy or sell energy in order to sort of meet their local demands apart from the exercise which is done by GCIL from the operation perspective. Coming to few good attributes or few expectations from a so-called good power network.

The first one is economics. Any planner or any operator would like to minimize the operation cost involved in the network or in the organization. Same goes true for power network as long as operation and maintenance cost are low, economic for the system is maintained. Efficiency is the next important attribute wherein apart from generation which is being generated and is not serving the loads, essentially it goes as I square R loss or power loss. That should be as minimum as possible so that the efficiency goes close to 100%. Theoretically speaking, it's possible, but practically speaking, no network is ever going to be lossless.

So there will always be some active power loss which will be endured, but then the efficiency, we can try to maximize it to the extent possible. Next few attributes are about stability, which is essentially about can the network voltage and frequency be maintained? Even when the power network is experiencing disturbances, for example, varying load conditions, the load is not a static or a stagnant quantity. It always varies with time. So with variation in load, can the network voltage and frequencies to be maintained is part of stability. If it is there, then the system would be stable.

Then there are also security aspects wherein The network or power network may undergo certain situations which are unforeseen. We power engineers call them as contingencies. And during these contingency situations, is it possible to maintain system normalcy? Now what is meant by system normalcy? It has all to do with three aspects basically. First, can all system loads be met by the net generation which is available? Point number two, Can this load balance or generation balance be maintained while not enduring any overloads or over current issues? And lastly, how well is the efficiency of system maintained while maintaining this load balance or what time frame can the system endure the overload or under load situations while maintaining system security is the question.

next aspect of security. So if these three aspects of load balancing, maintaining under load overload situations and time in which these under load overloads can be alleviated if those can be maintained then we call our network to be a secured network. Reliability is another attribute which aims at or which sort of emphasizes on that the network should have minimal interruptions minimal disturbances minimal loss of electrical power minimum loss of load while supplying electricity if that loss of load can be minimized a system would automatically become reliable. resiliency in case the system has undergone any disturbances or some part of network has become faulty or some natural disaster has happened wherein some portion of network has went through a difficult failure. How quickly can the system recover and still behave or operate in the normal situation is part of resiliency. Quality, if the voltage harmonics, current harmonics, voltage fluctuations, if they are minimal, the system tends to have a good power quality.

All these attributes that are there that are defined. They can be maintained or are being maintained through different algorithms tools which are there as part of energy management systems which are used for operating and controlling the power network at energy control centers. Coming to generation, typical system generation, we all know it's mostly being done at the three phase level. And if we talk about conventional generators or conventional three phase synchronous generators, then all these generators, the same is also true for DC generation. It tends to have a prime mover or a source of mechanical power which tends to drive the rotor or the synchronous generator and it converts this mechanical power into three phase electrical power.

Typical prime mover it can be either steam operated or hydro operated. In steam operation either the steam can be generated by thermal plants where coal is typically burned or it can be done in nuclear power plant through fusion reaction and typically in these sort of turbines the associated synchronous generator tends to have a cylindrical pole rotor with high revolution per minute turbines. The reason behind why the cylindrical pole rotor tends to have high rpm we will talk about in detail when we discuss the synchronous generator module in detail. Then we have typical hydro turbines whose rotation is at low revolution per minute or low rpm and typically they have salient pole rotor as the mechanical structure in the synchronous generator. So essentially typical alternator that we will discuss at length it would essentially have two distinct parts one is the stator which houses the three phase stator windings and then we have a rotor in which the coupling happens with the turbine and it essentially is a DC circuit carrying DC current.

The stator field is typically produced by the three phase currents in the three-faced armature bindings and the term synchronous generator gets its name from the notion known as synchronous speed. So, essentially the filter field in the air gap rotates at the synchronous speed and the same is also true for the rotor. The rotor being a DC circuit supply it also rotates at synchronous speed. So, essentially the rotor field and filter field in the synchronous generator both rotate at the synchronous speed and they are essentially locked to each other. In terms of power control the rotor excitation current tends to regulate or control the reactive power output of a synchronous generator whereas the turbine power tends to regulate the real power output of a synchronous generator.

Ideally speaking any synchronous machine can operate as both a motor as well as a generator. So in a motor essentially the mechanical power is the output and the input is the electrical power whereas in a generating mode the mechanical power is the input and electrical power is the output. Ideally speaking any synchronous machine or any machine for that matter rotating machine can operate both as generator as well as motor, but practically we tend to design our alternators or three phase synchronous generators to avoid

absorbing real power because of bidirectional protection element features available at the alternator level, which we will discuss if the availability of time permits towards the end of this discussion. Typical operating voltage or generation voltage is three-phase and around 225 kV line-to-line voltages.

Coming to the transmission level. why transmission is essential, necessary at all. If power which is being generated or generating stations, if it is being generated at around 20 kV and if we look at the history of Indian networks or the power networks which are there elsewhere in India. Typically these voltages were very low and there was a issue that power could not be transmitted to far off ends at low operating voltages because lot of power was being used up as I square R loss basically the efficiency was very poor. The reason why transmission network comes into picture is because the voltage level of 20 kV which is the typical generating voltage it is scaled up or amplified to higher voltages so that the I square are losses are minimum in order to do that the step up transformers come into picture which scale up the generation voltage level to high voltage of transmission system and these transformers basically power transformers they are highly efficient transformers Now, if we were to sort of have our loads consume power at 100 of kVs, which is the voltage scaled up from 20 kV to 100 kV by the step-up transformer, our loads could not consume power at such voltages. So, essentially, the 100 kV voltage level is further scaled down to 11 kV to 33 kV by step-up transformers.

And eventually, through use of distribution transformers, finally, we get the three-phase 415 volt or single-phase 220 to 230 volt supply. The loads form the most critical element of the entire power network. If there would have been no loads in the network, there was no need of having an electrical power network at all. So basically, they are the drivers behind the entire power network.

We have different forms of loads, industrial loads. They are usually supplied at the sub-transmission level, which is typically at 33 kV, three-phase, line-to-line. And it involves mostly induction motor loads, whose power function of both system voltage and frequency. We'll talk about it more in the power flow analysis module. Mostly such industrial loads consume high amount of reactive power so reactive power compensation is needed mostly at the sub-transmission level. Then we have the residential loads which are mostly heating and lightening loads and eventually with the renewables coming in we have lot of inverters and battery energy storage systems and EVs which are mostly power electronic loads and they're One of the demerits with such loads is that they tend to inject lot of harmonics, so lot of harmonic compensation is often needed.

Typical units of loads from the perspective of real power, we define real power in terms of watt. reactive power is defined in terms of volt ampere reactive and apparent power is

measured in terms of volt ampere energy is nothing but power into time so basically the unit of energy is watt hour and typically one unit or one unit which we define in terms of distribution network is typically nothing but one kilowatt hour where k is small in kilo. Aggregate load The pattern, it is that it typically tends to follow an annual duck curve or a typical daily load curve in the sense in the early morning hours of a typical day, the load tends to go up because everyone either goes to their offices or goes to the schools, basically a lot of heating load is required. Whereas typically around 12 noon or 1 o'clock it's a little relaxed period so load tends to go down while again in the evening time lot of heat lightning is required so people tend to come back from the offices so in the evening hours the load tends to again go up and finally it goes down in the night time so basically if I were to plot. the typical behavior of a load let us say in terms of P with respect to time then for a span of between 0 to 24 hours I would typically assume a peak in the morning hours and again a dip and probably again a peak in the evening hours and finally again goes to a dip in at the   end   of   the   day.

 That's how the duck curve or load curve happens and similar plot can also be done if we were to plot it annually because of weather variations during summers the loads tend to go up during winters the load again tends to go up while during spring and autumn the weather being pleasant the load tends to be at a moderate level so there is a way of how this load variation can be typically monitored or typically quantified and that's where these different indices come in wherein if you have to define load factor for a typical day And it is nothing but total energy consumed in 24 hours divided by the peak demand in 24 hours. Whereas the same if you were to define in terms of annual behavior, so the 24 hours gets replaced by the time or an annual energy consumed over a year and the typical time being 8760 hours in a year. We also have two other indices utilization factor and plant factor which essentially define the ratio between peak demand and installed capacity in UF whereas plant factor is nothing but annual energy generated divided by the installed capacity over the entire annual year. As long as these different indices, they are close to the highest possible value possible or I would say close to one to the extent possible or more than one, the system tends to have a good economics because it essentially indicates that the loads, their behaviors are more or less flat, our installed generations are operating at their maximum possible capacity because that's how the generation is supposed to make profit. So as long as load factor or annual load factor is as high as possible means the duck curve which   I   had   shown   earlier,   it's   almost   close   to   flat   or   being   flat.

 Whereas if utilization factor and plant factor are as high as possible means our generations are working at their maximum possible capacities. In terms of network protection, it is also essential because during falls or during accidental trippings, the unhealthy part of the network needs to be protected from the healthy part. So to have such a system in place, typically it consists of fuses, which were the conventional or classical devices. And over

time, these have been replaced by different relays and These relays need different sensors so these sensors basically they are called as instrumentation or instrument transformers which are different from power transformers and their purpose is to scale down the high voltage or high current levels to low voltage or low current so that this low voltage or low current can be used by the relay to sense the fault and finally through the relay the circuit breaker get their trip signals which trip the unhealthy part from the healthy part of the network a good protection system should be reliable fast accurate and it should be as cheaper as possible so these are few attributes for a good power system In terms of analysis in power networks, we can categorize this analysis or discussion into four typical parts. Coincidentally, we will be talking about or discussing about the three important analysis and   one   we   could   not.

 So the first one, which we would discuss as part of load flow analysis or power flow analysis is steady state analysis, in which it is assumed that the power network is in steady state, no changes are happening in the network. and the system or the network can be modeled through several algebraic equations and network is represented in the simplest best possible manner. So that's how the lumped system representation comes in. The next part of analysis is transient analysis which is essentially a part of analyzing that after a electromechanical disturbances like fault occurrence of fault generation tripping or line switching or load switching is the system stable enough or not. So this would form part of our transient outer angle stability which is going to be the part of the last discussion.

 In order to understand the dynamics of how the system is enduring these dynamical changes, there is also a need to have certain differential equations along with algebraic equations and the techniques of understanding or doing this transient analysis is definitely going to be different from traditional analysis because we have additional differential equations. The next part is sub transient analysis, which is essentially a fault analysis exercise, I would say, which we are going to discuss in the second last module of this particular course, in which the time period of interest is from is a few milliseconds and the purpose is to figure out that right after a disturbance or a fault what is the maximum current or what is the what is the maximum voltage that that could have happened and this aids in deciding or figuring out the settings of different relays and circuit breakers are in place so it's basically a pure electrical analysis there are no mechanical interactions involved The last analysis which unfortunately we could not discuss as part of this course is ultra-fast travel analysis in which the idea is that during an event of lightning, lightning is a natural event and electrical network being no exception also faces this lightning strikes almost every day I would say. At least some part of the network experiences lightning strikes every day, so during lightning phenomena can be explained as energy exchange between network inductance and network capacitance and this energy exchange which happens happens almost at the speed of light. So time period if we were to see it is in order of few

microseconds to few milliseconds and to understand this phenomena of how lightning analysis or lightning strike happens We make use of coupled linearized differential equations as well as certain distributed parameters and the output of this analysis helps in understanding how do we design our system so that during lightning the system security, stability, integrity is not at stake. So in order to sort of summarize, if I have to do analysis of a given network at different time frames, basically what I would do is I would first figure out what are the components of the system and how do I model them appropriately so that the model typically represents the either the steady state or either the transient state or the sub   transient   state   of   the   network.

 So, system modeling is the first important step. After defining the system model what electrical equations could be differential equations, could be algebraic equations, what equations define that model and having obtained these equations then the next step is to figure out how do I solve these equations. So, figuring out a suitable numeric solution technique is the next step and having obtained those solution techniques, lastly after I have got my solution, how do I analyze that solution to sort of aid in decision making and planning. So these are the four simple generic steps behind any study that we would be aware of during this discussion, be it power flow analysis, fault analysis or stability analysis, all those analysis will essentially involve these four simple steps. In the next lecture, we will start with our first preliminary discussions. Basically, this discussion or this lecture was essentially giving preliminary background of what we can expect from this course.

 We will discuss at length about generation, transmission, transmission line model, and then few studies to transient and sub-transient analysis. First module that we will take up is basic circuit principles, which is basically going to be a recapitulation of the prerequisites that would be needed for you for understanding these topics. So that's where our first preliminary discussion would be, is all about phasor diagrams in the next lecture. Thank you.