Operation and Planning of Power Distribution Systems

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Lecture - 29
Reconfiguration of power distribution networks

So, in this part of the lecture, I basically talk about Reconfiguration of Power Distribution Networks ok. So, I kept this is on module 6, but this is something different this topic; is bit different than power distribution system planning ok. So, I will discuss these different aspects of reconfiguration starting with what is power distribution network reconfiguration.

But before, I should tell you that this topic is one research paradigm ok. So, this is one area of research in which many people are working ok. And there are hundreds of paper, thousands of paper, you can get on power system reconfiguration; most importantly that power distribution network reconfiguration. And here I will try to give you a glimpse of this idea, that what is the research going on this power distribution network reconfiguration ok.

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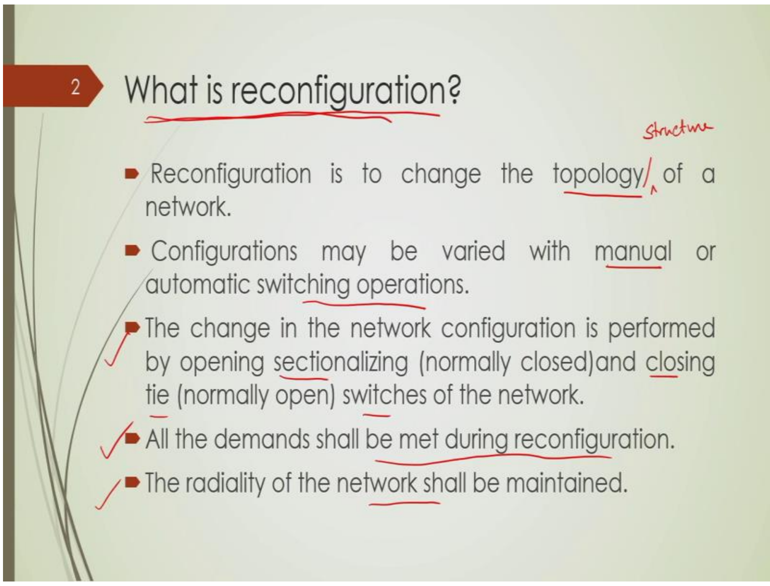

So, let us start ok. Now, first question is what is reconfiguration? What do you mean by reconfiguration? So, reconfiguration is basically a change of network topology or structure ok and this reconfiguration may be varied with manual or automatic switching operations ok. And this is change in network reconfiguration. So, basically in one word, the reconfiguration of distribution network is to change this network structure of topology by changing the status of sectionalizers and tie switches ok.

As you have seen in my last lecture, I was talking about the placement for sectionalizing switches and tie lines ok. And as you know that, sectionalizers or sectionalizing switches are normally closed switches ok. They are normally closed switches ok. And their operation can be either manual or automatic ok.

And tie lines are normally open switches ok. So, we have a number of sectionalizing switches and a number of tie lines in a typical distribution network ok. And in my last lecture, I have shown you some examples of 100- and 54-node systems by placing this sectionalizing switches and tie lines in different locations ok.

So, that was part of this power distribution network planning because our goal was there how to locate/ how do we locate this sectionalizing switches and how do we locate this tie switches or tie lines ok. So, the locating some device optimally is a part of distribution system planning ok.

But here our goal is effective usage of those sectionalizers and those tie switches such that you get a desired objective fulfilled ok. So, it is a kind of operational optimization. So, here I do not need any sort of capital investment as such because we are assuming that a network is equipped with sectionalizing switches, a network is equipped with tie lines or tie switches. And here our goal is to optimally determine the status of the tie switches and the sectionalizing switches ok.

So, as you can see that sectionalizers are normally closed switches, but we can open it if we have any necessity. Similarly tie lines are normally open switches, but we can close them when the situation demands. So, the status of sectionalizing switch can be on and off. Similarly the status of a tie line can be on and off.

Now, here in the reconfiguration on distribution networks, we will optimally determine the status for sectionalizing switch and tie line. So, that it can result in the change of network topology. How do we change the network topology? I will come to that ok. So, reconfiguration is basically the change of network configuration by opening the sectionalizing switch and closing the tie switches closing the tie switches or tie lines ok.

Now all the demand, one constraint of this reconfiguration is that all the demand should be met during the reconfiguration. That means, whichever load was connected before the network is reconfigured, those many loads would be connected and they these will get supplied ok and that is the one of the constant and also the radiality of the operation of the network will be remain intact. So, this is another constraint that we will keep the network topology as such radial as similar to this planning problem ok.

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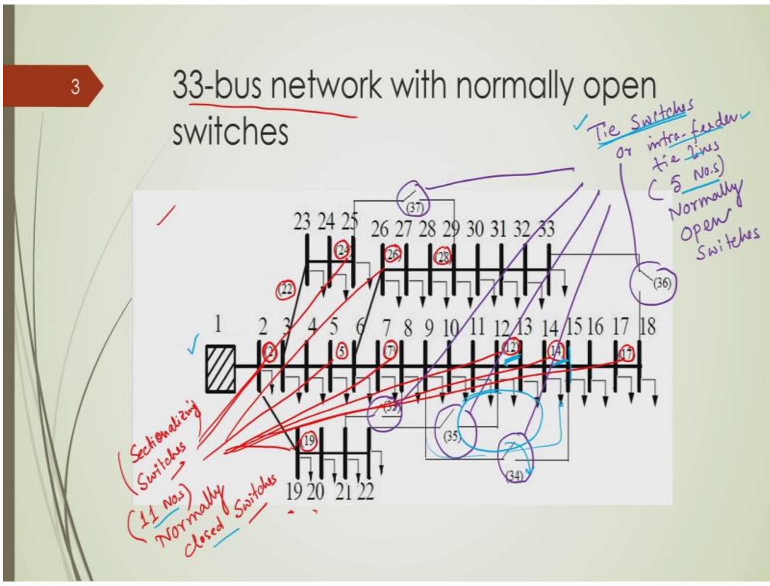

Now, this is a typical 33-node system where you can get an idea that what is reconfiguration and what is the goal of the reconfiguration. So, in that network, you can see there are many sectionalizers and these sectionanalizers locations are marked with these numerals which are kept within this parenthesis. So, these are the locations of sectionalizer; so these are the locations of sectionalizer, so these are the locations of sectionalizer.

So, these are section, so these are the locations for sectionalizers which are predefined which are already planned. So, these are the locations for sectionalizers which are predefined which are predefined. So, these are the locations of sectionalizers ok.

So, how many sectionalizers we have here? We have in this particular lateral we have 1, 2, 3, 4. Sectionalizers in the main trunk feeder we have 1, 2, 3, 4, 5, 6 sectionalizers, so total 10. And in this lateral, we have another sectionalizer located in between nodes 19 and 20 ok. So, total altogether, we have 11 sectionalizers; so, 11 numbers of sectionalizing switches; 11 numbers of sectionalizers switches that you can see ok. And in addition to that, we have some tie switches. We have some tie switches which are marked, with this; these are tie switches, these are tie switches ok.

So, how many tie switches we have we have five tie switches? So, these are the tie switches or intra feeder tie lines, intra feeder tie lines. So, we have 5 numbers of intra feeder tie lines; 5 numbers of intra feeder tie lines ok and they are normally open switches; they are normally open switches. Whereas, you can see that the sectionalizers are normally closed switches ok.

So, in this example, you can see we have 11 number of sectionalizing switches which are normally closed switches and we have 5 numbers of intra feeder tie lines or tie switches. Why I am calling intra feeder tie lines? Because as I have seen that normally tie lines are kept to tie between the adjacent feeders ok, but here this is a single feeder network as you can see. So, these switches can be called as intra feeder tie lines or it can be simply called as tie switches ok.

Now, what is the purpose of this tie switches? The purpose of this tie switches is that, we can close this tie switches we can close these ties tie switches. As soon as you close the tie switch, for example, if you close this tie switch then what will happen then this here you can see there would be a loop formed ok and in order to maintain the radiality of the network I need to open either this normally closed switch or sectionalizer or this normally closed switch.

So, that this loop will get loop will break ok and thereby the radiality of the operation radiality operation of the network will remain intact ok and that is what our goal for doing this reconfiguration. So, in that case this power of this 15 node number 15 will come through this 9 via this tie switch ok.

And there will be a break in this loop either by opening of this 12 number switch indicated by number numeral 12 or by opening this sectionalizer indicated by numeral 14. So, this is the main goal for reconfiguration ok. In reconfiguration, we purposefully change the network topology or network structure in order to achieve certain goals ok.

Now what are the goals you will get by doing this type of reconfiguration, these are mentioned over here that why should we change the network structure or network topology you can look at this. These are the goals or these are the benefits that one can draw from this reconfiguration of distribution network.

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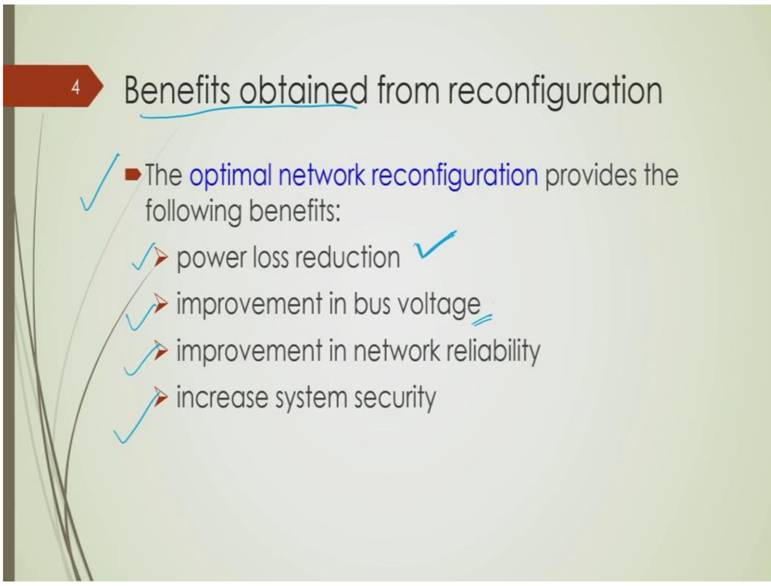

What are the benefits? One benefit is power loss reduction ok. So, we can reduce the power loss of the whole network. Power loss of the whole networks means it is the sum total of the losses taking place in a different distribution lines or distribution branches. So, if we get that overall power loss of the network or sum total of the power loss gets reduced then we can; obviously, go for this reconfiguration ok.

So, one of the benefits or one of the goals to achieve this reconfiguration is to reduce the power loss ok. Second is to improve the bus voltage. So, sometimes you have seen that I have shown you the bus voltage profile in module 4 and you have seen the furthest nodes of a distribution network suffer from this under voltage problem because of this voltage drop ok.

Now, by doing this reconfiguration we can alleviate, we can reduce the overall maximum voltage drop of a particular feeder or we can improve the bus voltages of the furthest nodes ok by changing the path. Similarly, we can improve the reliability and we can also improve the system security particularly voltage tablet ok.

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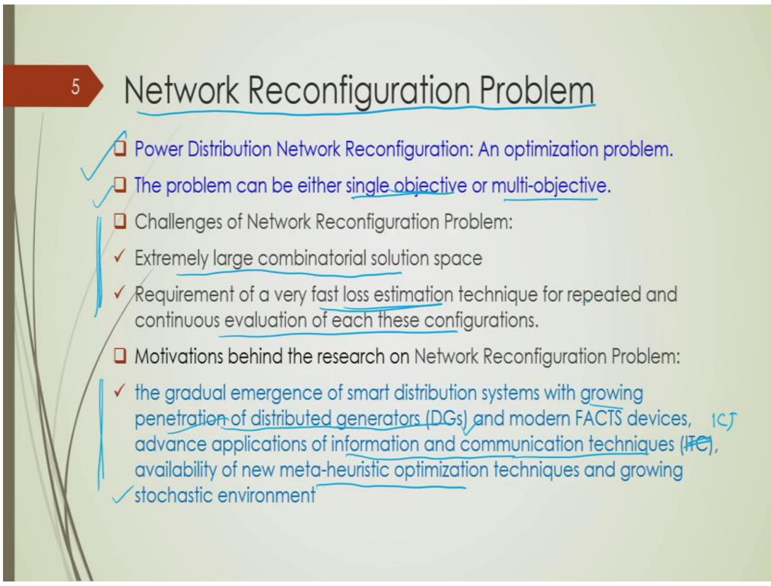

Now, the network reconfiguration is essentially an optimization problem. So, similar to power distribution network planning, power distribution network reconfiguration is essentially an optimization problem. Since it is an optimization problem, we can formulate this way either with a single objective optimization problem or multi-objective optimization problem.

Now as you know the single objective optimization problem is having with only one objective function which we need to optimize under certain constraints ok. And in multi-objective optimization problem, we have multiple objective functions which we need to simultaneously optimize under certain constraints ok.

So, this problem can be formulated either by single objective or multi-objective problem. Now what are the challenges we have in this reconfiguration problem? It is an example of extremely large combinatorial problem, where suppose we have a distribution network having 10 numbers of or 10 or 11 numbers of normally closed switch and 5 or 6 numbers of normally open switches.

Now, in order to determine the optimal combination for switching status, so as to achieve the certain goal or certain goals is a kind of combinatorial optimization problem and there might be a huge number of combinations exist. So, that is one of the complexity of solving this particular problem.

Similarly, we have to estimate. So, this needs a fast loss estimation technique and the repeated and continuous evolution of this configuration ok. Now what are the motivations behind this network reconfiguration problem particularly in present era or in future era, where we are expecting that our networks will be equipped with more communication system, advanced communication system, a better way of measurements and also it will be connected to this information and communication systems.

Then this whole thing should be more practical to or more practically feasible to use. For example, you have seen that distribution networks are gradually having growing penetration of distributed generation units. These things I will talk about my next module and also it is going to be equipped with more number of and more advanced information and communication techniques, ICT.

And also availability of meta-heuristic optimization techniques which can solve a large combinatorial problem with a given degree of accuracy ok, those are the motivation factors for doing research in this particular domain ok.

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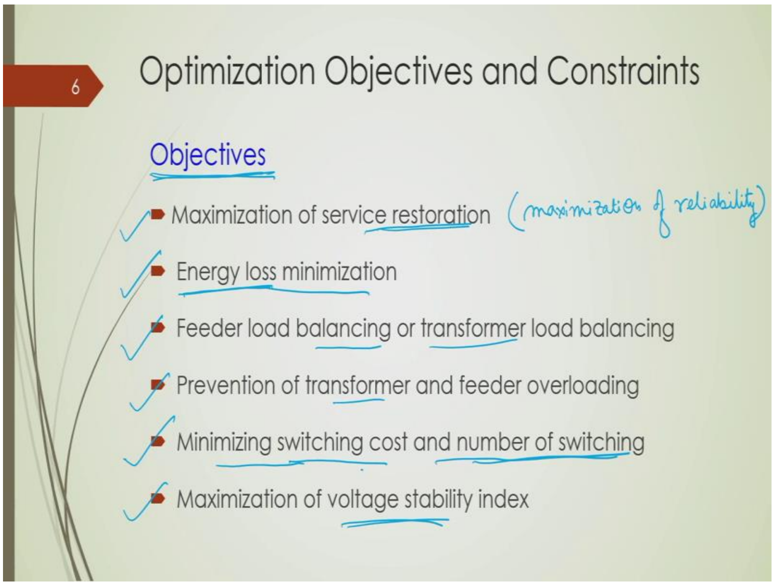

Now traditionally as I said, already we have a quite volume of literature for a distribution network reconfiguration problem. And there are several objective functions formulated, in different approaches or different journal and conference papers. This includes this maximization of service restoration which is somewhat similar to a reliability objective.

So, maximization of service restoration is somewhat similar to maximization of reliability of the network maximization of reliability of the network ok. Of course, this power loss or minimization or energy loss minimization is an important objective that we should consider for solving any type of distribution system, planning or reconfiguration problem.

Similarly, sometimes this reconfiguration is done in order to balance the loads among different transformers in a particular under a particular substation. And also this reconfiguration problem is exercised in order to reduce, the overloading of the feeders and the transformers under in a particular substation.

And while doing this reconfiguration, there is a one important thing that many people consider. This is minimization of the switching cost and the number of switching in a particular day or in a particular time period, which is very essential, because the switching of this normally open switch and close switch will associate with certain amount of cost. Also this voltage stability is another objective many in which is considered in many of the papers or many of the approaches.

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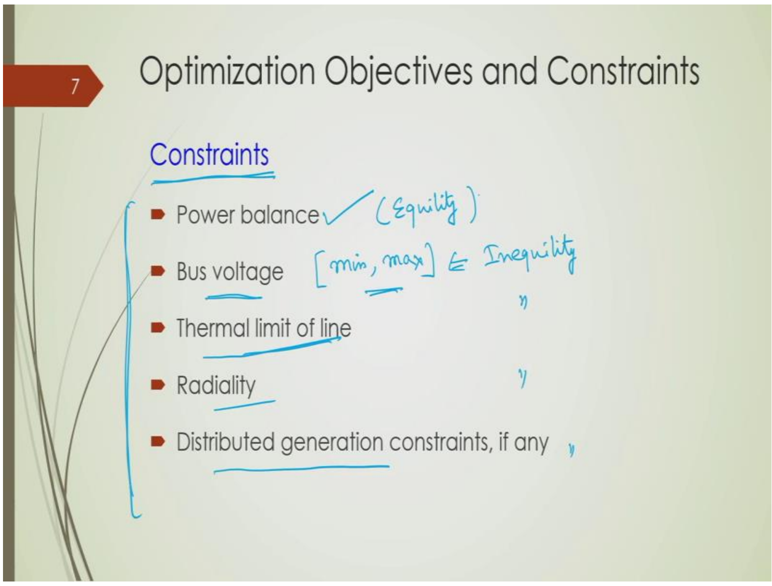

And these objectives are optimized under certain technical constants. One is of course, power balance constraint which is an example of equality constant that you have seen in case of distribution system planning ok. So, what is power balance constraint? It is to balance the power demand of the loads and the power supplied through the substation ok.

So, this is; obviously, something that one should ensure and this is normally ensured through the use of this load flow or forward backward sweep load flow, if this network operates in radial ok. Similarly, bus voltage constraint is there, so we have to keep this node voltage or bus voltage in a typical distribution network within minimum and maximum limits.

So, this is something, one needs to understand and these are the examples of inequality constraint inequality constraints ok. Similarly, thermal limit of line: it is also an inequality constraint radiality of line should be intact this is also inequality constraint. And if there is any distributed generation unit then it is penetration is also another constraint which is considered in different props this is a kind of inequality constraint.

So, similar to power distribution system planning here also we have a number of equality and inequality constraints and our goal would be to optimize the objectives or multiple objectives under these constraints ok. So, this is also essentially an optimization problem.

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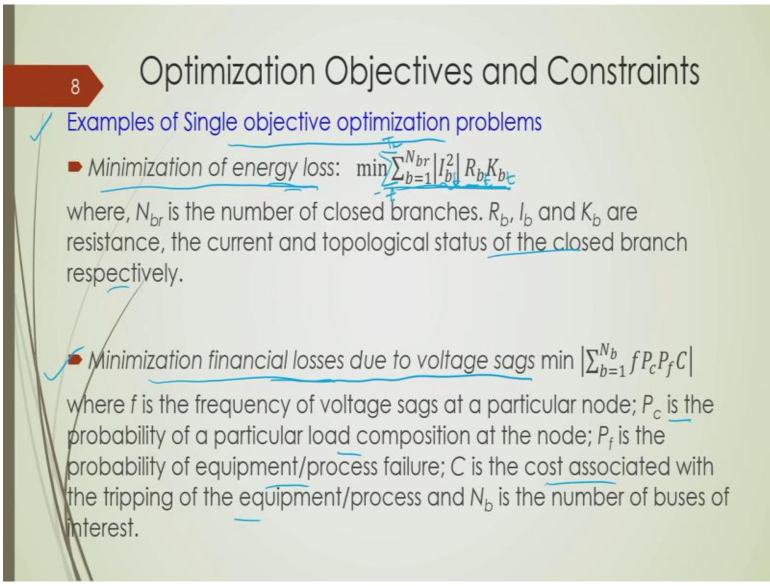

So, here you can see some of the examples of single objective optimization formulations which are done in different works. So, minimization of energy loss is, as I have shown you, one of the objective functions formulated in many of the papers, in fact most of the paper. Because, this is also a main advantage of doing reconfiguration of a typical distribution network ok.

And this is the mathematical expression for minimization of energy loss where you can see this I square R of individual feeder branch is considered and according to this status of these switches. And this is minimized over a certain period of time and that will give you the minimization of energy loss ok.

In fact, this should be minimized with T is equal to 1 to certain time horizon and all these things will be this, T is equal to, it is starting from T is for to certain horizon and all this should be subscript T ok. Similarly, minimization of financial losses due to voltage sag is considered to be another objective function in a single objective optimization problem, for this network reconfiguration.

And this includes this loss due to this voltage sag which is also function of the probability of particular load, composition in a particular node and also probability of equipment failure cost associated with the tripping of the equipment or process ok.

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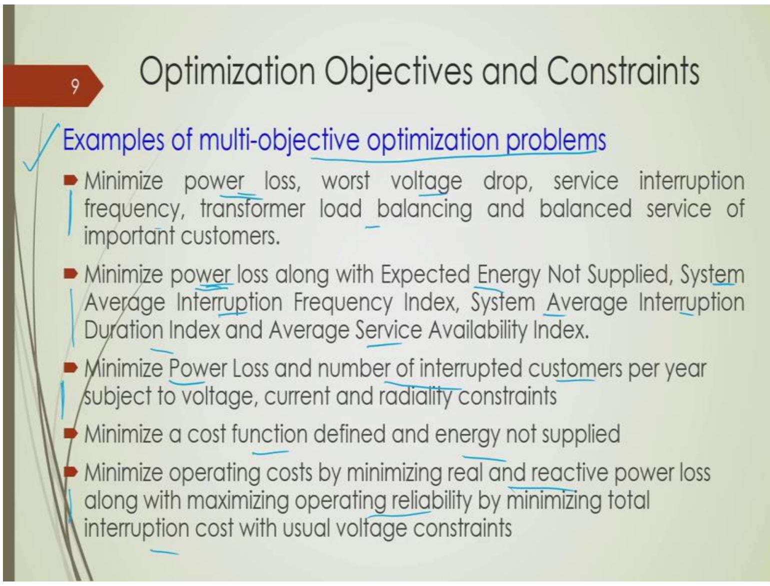

And there are also many approaches reported which are multi-objective optimization approaches in which several objective functions, where considered and these objective functions are optimized by considering multi-objective optimization approach ok. There are different multi-objective optimization problems formulated which include different types of objective functions formulation.

For example, minimization of power lost, voltage drop, service interruption, frequency load balancing etcetera in one of the approaches. In another approach along with this minimization of power loss, expected energy not supplied that is EENS that is similar to ENS which is taught in the reliability module so that you by reducing or by minimizing that ENS you can maximize the reliability of the network and also there are several other reliability indices considered; for example, System Average Interruption Frequency Index that is SAIFI, System Average Interruption Duration Index that is SAIDI and Average Service Availability Index that is ASAI; all these indices I have taught you in module 3.

So, these indices are reduced or these indices are minimized along with this power loss. So, that the network that we are trying to get after reconfiguration should be or should have a better reliability as well as a reduced amount of power loss ok.

Similarly, another approach along with this power loss minimization is this, because you can see power loss minimization is a common objective used in most of the approaches. But apart from that this number of interrupted customers per year that is also a kind of reliability objective is considered and these objectives are minimized simultaneously.

Similarly, this cost function and ENS are considered in one of the papers and another paper along with these losses, this reliability maximization by minimizing the total interruption cost is considered. That means, this approach is similar to this optimization of energy loss as well as the cost and reliability ok.

So, these are the some of the works you, but this is not an exhaustive list. So, you may get different other works also where different objective function formulations and different approaches used for solving those problem ok.

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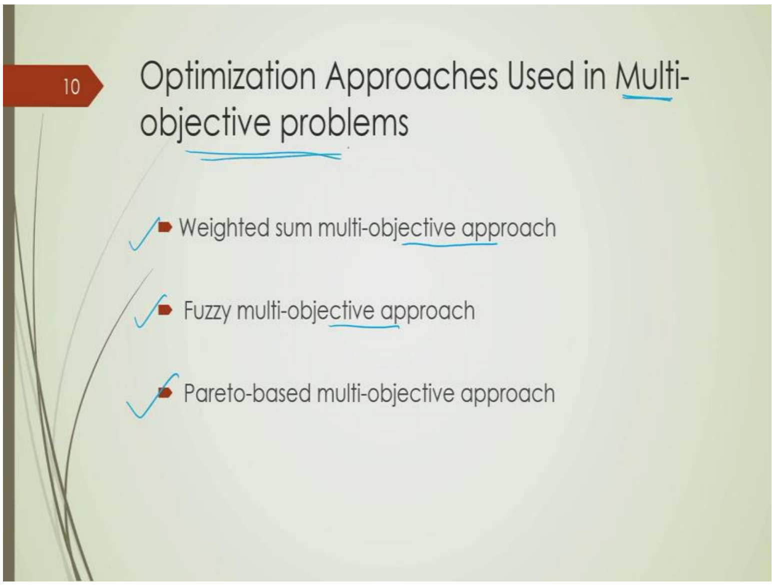

And as you know, in multi-objective optimization problem, we have three different approaches. One is called weighted sum multi-objective optimization approach, already I explained in couple of lectures in a couple of last lectures.

Also one is fuzzy multi-objective approach where the concept of fuzzy set theory is used or fuzzy membership function is used. Another is Pareto-based multi-objective approach which is taught in last two lectures ok. So, these are the traditional ways for handling this multi-objective optimization problem.

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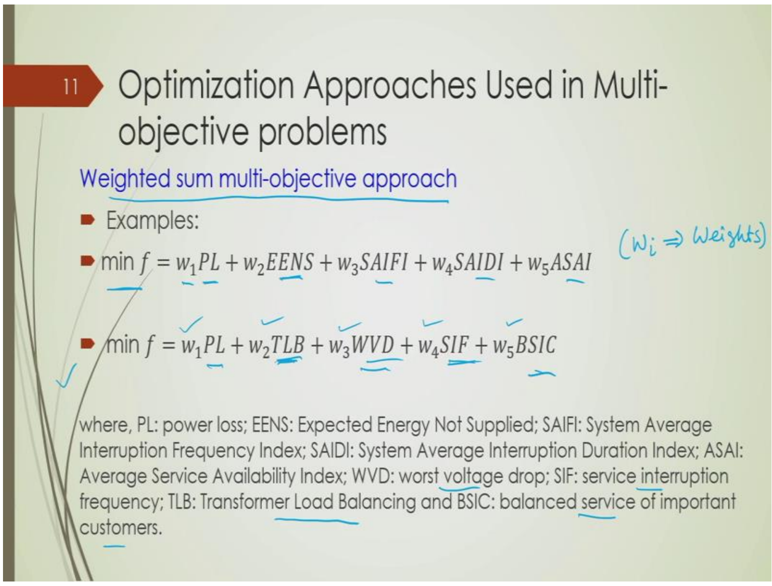

And as you know, this is a typical approach which can be categorized as weighted sum multi-objective approach, where different objective functions are aggregated with weight. So, the here this W, this W i, these are weights assigned to different objective functions which include power loss, which include ENS, SAIFI, SAIDI ASAI ok.

Here these objectives are of different objectives and they are aggregated with respective weights to in order to form an aggregated objective function. Similarly, in another approach, you can see this along with this Power Loss that is PL this TLB that Transformer Load Balancing is considered to be another objective, so this index the TLB is basically for balancing this transformer load.

And also there are different other objectives which are aggregated which includes service interruption frequency, worst voltage drop or here in means the highest voltage drop is considered to be another objective, which needs to be minimized along with this power loss.

Similarly, this balanced of service of important customers is another objective and all the objectives are aggregated with respective weights. So, W 1, W 2, W 3, W 4 and W 5 represent the respective weights for all these objective functions ok.

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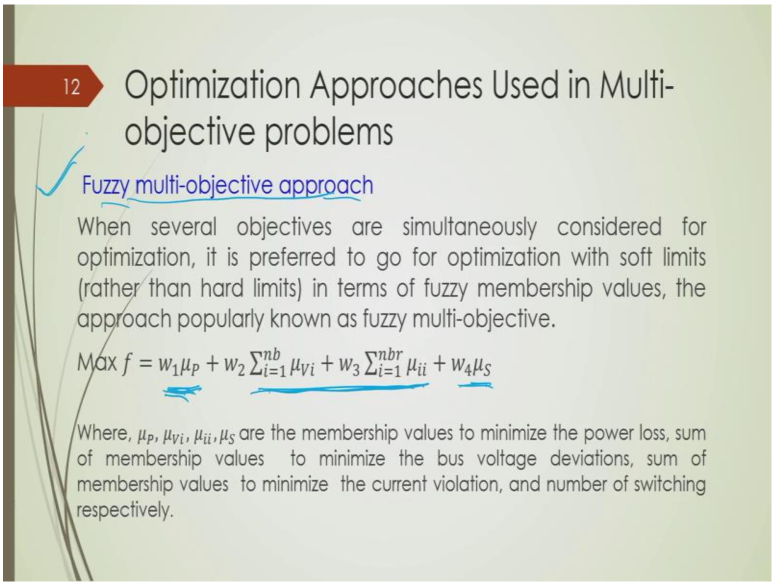

This approach that fuzzy or multi-objective approach is a similar kind of aggregated weighted and aggregated approach of or rather the similar kind of approach where this individual different objective functions are weighted, to form an aggregated optimization objective function.

But, why we call it fuzzy multi-objective approach here? Basically the one is main objective that is power loss minimization and other two are basically the constraints. And these constraints are fuzzified with a membership function and it is aggregated; they are aggregated with this main objectives that is the power loss and minimization of number of switches number of switching operations. So, these are two main objectives which are aggregated with the constraints and these constraints are represented by fuzzy membership function ok. So, this is one of the approaches authors called as a fuzzy multi-objective optimization approach.

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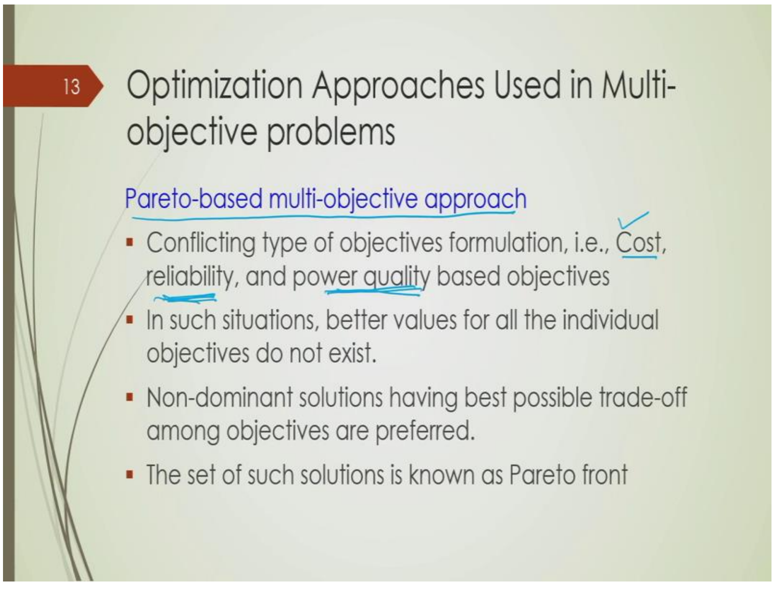

And as you know Pareto-based multi-objective optimization approach I discussed in detail in last two lectures, where we will be using simultaneous optimization of multiple conflicting objectives or multiple objective functions which conflict with each other ok. For example, there are many objectives as you have seen which can be categorized as cost function reliability objective and power quality based objectives. In fact, this power loss minimization, it is a kind of cost optimization because by minimizing this cost of energy loss we are basically minimizing the expenditure of the utility ok.

So, it is categorized as cost optimization and similarly you have seen different reliability indices are considered to be different objective functions which include ENS, SAIDI, SAIFI, ASAI etcetera these are categorized as reliability objectives. And there are some power quality based objectives and these objectives conflict with each other.

And Pareto-based approach is basically used to solve these objectives simultaneously ok. And Pareto dominance principle is used in order to find a set of non-dominated solutions which will not dominate or which you will neither dominate or not get dominated by any other solution and as you know a set of non-dominated solutions or a set of optimal non-dominated solutions is called Pareto optimal solution and if you plot this Pareto optimal solution we call this as a Pareto front ok.

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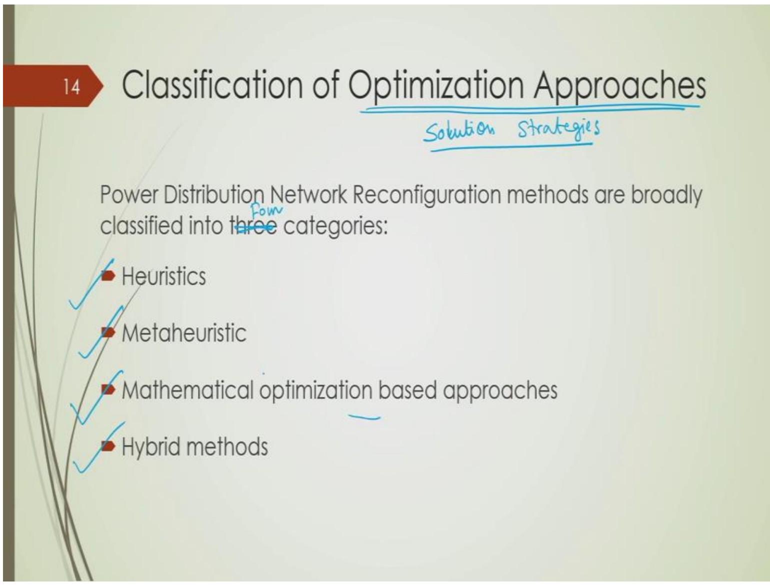

Now, this is this similar way we have seen in the last few lectures that people have used this Pareto-based approach to solve different kinds of reconfiguration problem or different reconfiguration problems with different objective functions and different solution. Now here we will talk about this optimization approaches or solution approaches or solution strategies ok.

Now, there are many types of solution strategies used in solving this reconfiguration problem and we have categorized them into four categories: One is heuristic approach, another is meta-heuristic approach, another is mathematical optimization based approach, another is hybrid approach which uses this different combination of mathematical approach and metaheuristic approach ok.

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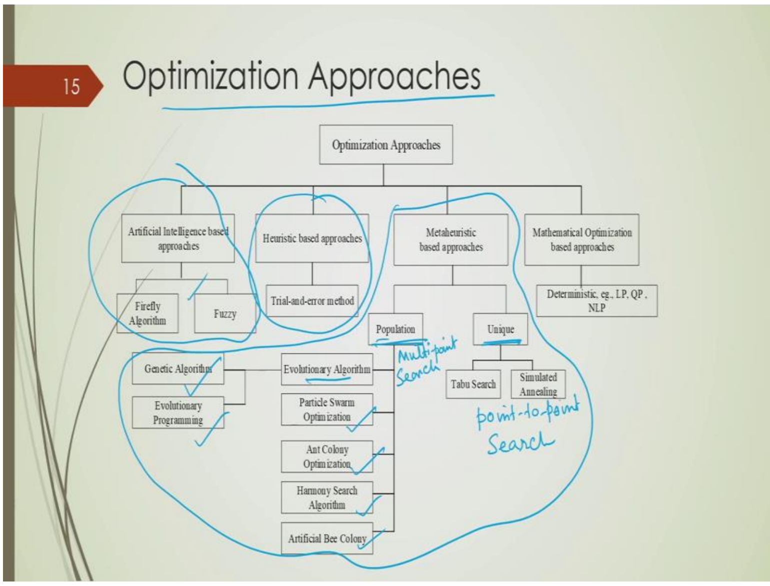

And this classification tree will give you a glimpse of different approaches used in solving this reconfiguration problem. You can see that one you know category belong to this artificial intelligence based approach, which include fuzzy based approach as well.

Another is a heuristic based approach which is nothing, but trial and error method or problem specific heuristics used for solving this problem. Another category is metaheuristic approach which is a bigger category where are different types of metaheuristic approaches used, which can be classified into two groups: one is population based approach, another is point search technique. So, this is point-to-point search technique and this population based is basically multi-point search technique.

And under this population based approach, you get evolutionary algorithms for example, genetic algorithm evolutionary programming or maybe particle swarm optimization, ant colony, harmonic search, artificial bee, and so on and so forth. So, there are many metaheuristic approaches reported last few years and there are many papers where you can find these approaches are used in solving this reconfiguration problem.

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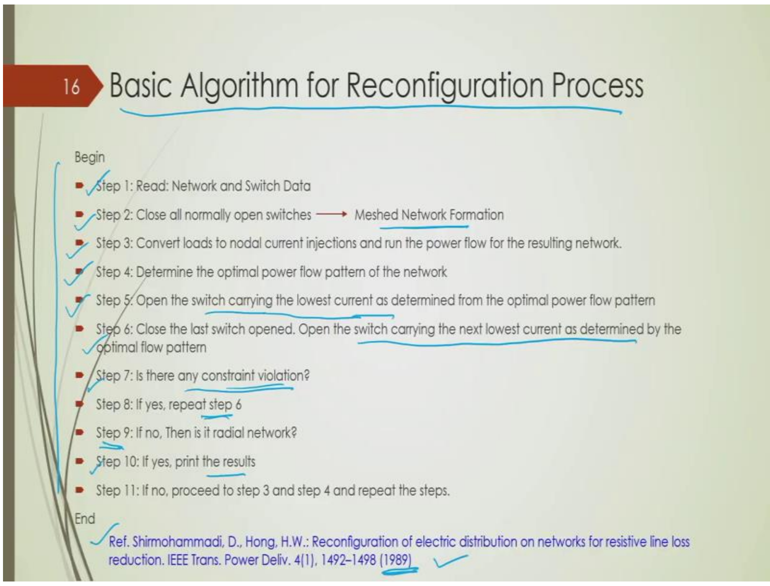

So, here you can see a basic algorithm for reconfiguration problem; for solving this reconfiguration problem which is one of the first kinds of solution strategy. For reconfiguration problem published in 1989, long time ago more than 40 years ago, it is proposed by these authors. And according to this algorithm, it is an iterative algorithm where step-wise different operations are mentioned: step 1 is reading this data, then step 2 is to close all this normally open switches or all these tie switches thereby this will create a mesh network. And then, convert these loads to the nodal injections and perform the power flow, then determine this flow pattern of the network or power flow pattern of the network. Then, heuristically open the switch which is carrying the lowest current or lowest power flow ok and close this last switch open and open the switch carrying the next lowest current and so on. So, in step ,7 a constraint violation is checked, if there is any constraint violation then we will go to step 9 otherwise step 6 will be repeated ok. And in step 10, we can see that it is a result of a radial network this will print the result. So, basic philosophy of this algorithm is by closing all these tie switches a radial network is firstly, converted to a mesh network ok and thereafter power flow is performed.

And after performing the power flow the branch or line carrying the lowest current or lowest power flow is identified and it is kept open. And we will repeat the process until and unless that the network becomes a radial network ok. This is a one of the, you know first kinds of approach for this solving this reconfiguration problem.

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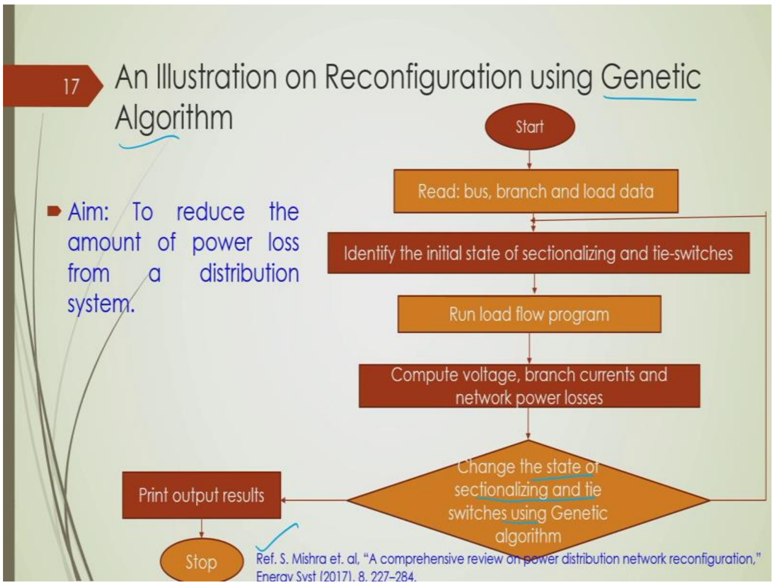

But there are several others approaches available, for example, in this paper, you can see a genetic algorithm based approach is used, where basically this state of this sectionalizing switches and tie switches are determined through a genetic algorithm ok. And how this genetic algorithm works etcetera you need to study more bit on this particular solution aspect.

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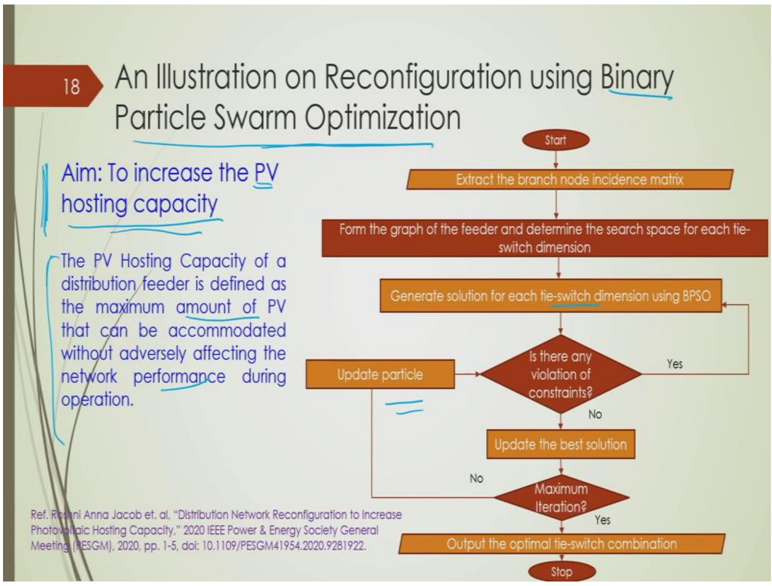

Similarly, in another work, particle binary particle swarm optimization is used and their objective was to increase the PV hosting capacity. This approach is used for active distribution networks. Now, what do you mean by active distribution network? When a distribution network accommodates certain distributed generation within it, then it becomes an active network.

And the objective function formulation is PV hosting capacity; PV stands for photovoltaic. Hosting capacity is basically capacity of distribution feeder of withstanding or accommodating the maximum amount of PV generation, which will not affect, which will not adversely affect the network performance. This, I will discuss in detail what is PV hosting capacity in the next module.

But this is a different objective function formulated in order to identify the states of the, or status of the tie switch and this sectionalizing switch ok. And it is solved by using binary particle swarm optimization algorithm, which is also taught in the last lecture. It is a variant of particle swarm optimization which can be used for those problems which involve binary decision variable or binary optimization variables ok.

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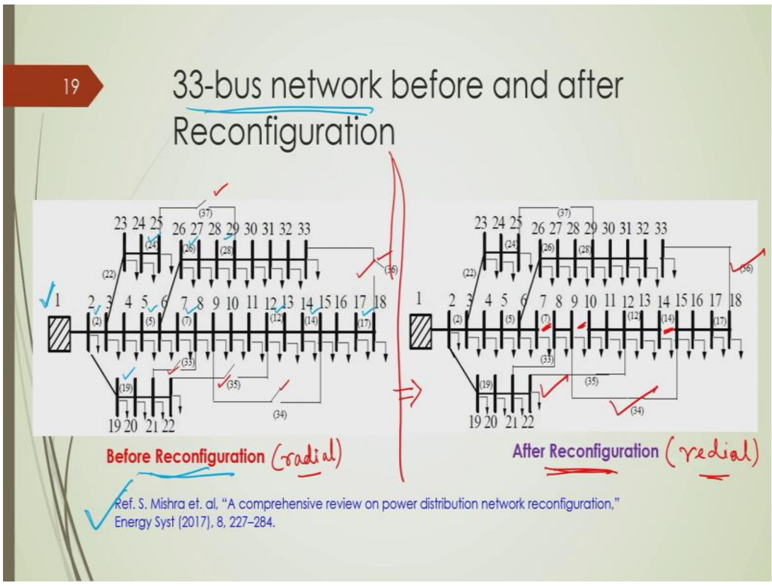

Now, I can show you a typical solution that is provided by this particular paper. So, this is a network topology before this network reconfiguration operation is carried out and this is a simple 33-bus network/ a 33-node network, you have seen many times ok. This is the case of single feeder network. So, at node 1, we have the substation and all other of load nodes; all other of load nodes ok.

And here we have, these are the normally closed switches; these are the normally closed switches. And the normally open switches are these; these are the normally open switches, which I have shown you in the very beginning. And here our goal is to identify the optimal status of those sectionalizing switches and tie switches so that we can achieve a certain objective.

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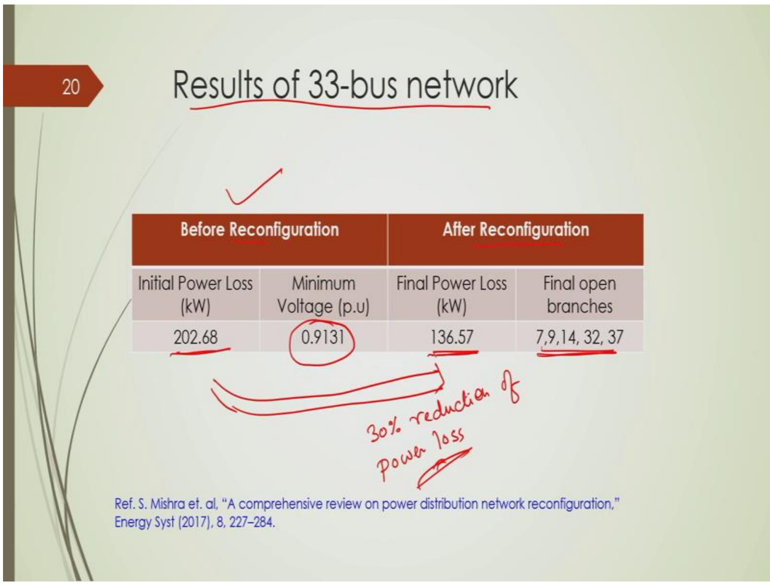

One of the objectives is of course, this power loss reduction or power loss minimization ok. So, after performing this reconfiguration approach it gets this topology is changed to this topology, which is shown in the right half of this figure where you can see some of the normally closed switches are opened. For example, this switches which are located at this branch 7, switches which are located at here, which is at branch 7, and 1 is here, another is somewhere here which is at branch 14.

So, there are some switches which are normally closed switches and there are some normally open switch, that is some of the tie switches are closed. One is this, one is this, one is this ok, but you can see and you can check the whole operation of the network or whole network remains radial. So, this network was remaining radial and after reconfiguration also network remains radial.

And this you know reconfiguration operation is performed under a certain loading condition; under a certain loading condition. And if the loading conditions change, then obviously, that this reconfiguration will no longer be optimal one. And another reconfiguration problem needs to be initiated to find out the optimal reconfigure network for that particular loading condition.

So, basically this reconfiguration depends upon the loading condition as well ok. And here, you can see that this reconfiguration results in this power loss reduction ok. So, before reconfiguration the power loss of the network was 202.68 kilowatt and after reconfiguration power loss becomes 136.57 kilowatt.

So, it is almost, in fact more than 30 percent reduction of power loss, so 30 percent reduction of power loss. So, here we get 30 percent reduction of power loss ok, which is very important, which is very important and particularly during peak load condition when power loss is also very high. Due to the initiation of this type of reconfiguration approach, one can reduce a huge amount of energy loss huge amount of energy loss ok.

And these are the branches which are kept open and of course, some of the tie switches are closed already I have shown. And one thing is also you can see that this minimum bus voltage, which was 0.9131 per unit; this also will get improved as the power loss is reduced or power loss reduction means voltage drop reduction which improves the voltage profile as well ok.

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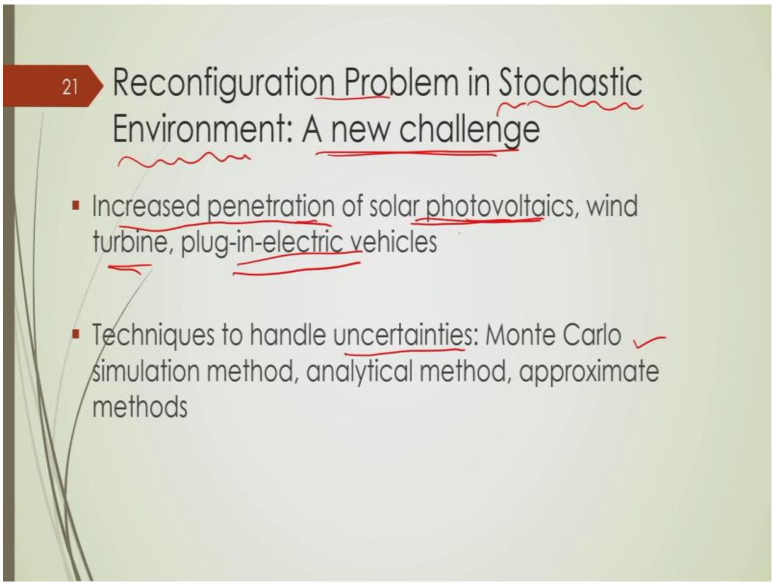

Now, these are the some new challenge for reconfiguration problem, one is a stochastic environment what do you mean by stochastic environment? Now due to this increased penetration or increased accommodation of this different kinds of nonrenewable sources, like solar photovoltaic, wind turbine also with different types of loading like plug in electric vehicles which are charged in its typical charging station.

So, this is changed this distribution network operation completely ok. And basically this generation of these photovoltaics, wind turbine, they are intermittent and therefore, they will undergo a wide variation ok. And similarly, if we have any charging station in a typical distribution network it becomes a load whose behavior also is not completely known to us. When something is unknown and when something is intermittent then we cannot use these normal approaches to solve this problem. And we need to have some special approaches which can handle this uncertainties, which can handle some sort of randomness and these are the some of the approaches like Monte Carlo simulation approach and some of the approaches traditionally used or should would be exercised in future investigation ok.

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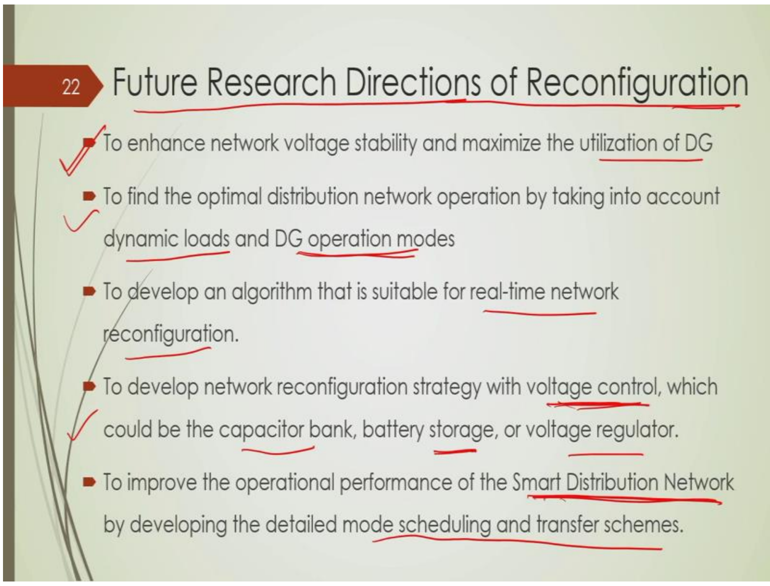

Now, in this slide, before I conclude or before I finish this part of the lecture, you can see future research directions for this network reconfiguration problem. So, first of all, this is to enhance network voltage stability and to maximize the utilization of DG that is why you can see that PV hosting capacity is kept as one of the objectives in one of the approaches I have explained ok.

Because, the primary goal is nowadays to integrate as much as, or to utilize as much as renewable energy sources as we can have ok, now considering this network reconfiguration problem needs to be formulated. Similarly, this optimal distribution network operation by taking into dynamic loads and DG distributor generation operation is another challenge ok and. So, not only for utilization of DG, but their presence will make some operational challenges.

Similarly, real utilization of this algorithm for real time network reconfiguration because, as I have told you that network reconfiguration should be applicable or for different loading conditions. So, it may so happen in a typical day, we need to run it for several times, depending upon the predicted loading condition for next few hours.

And accordingly this optimal status of the switches should be determined and they are they should be operated accordingly ok. Similarly, this reconfiguration strategy along with this control voltage control and if we have any sort of reactive power compensators. For example, capacitor bank if we have any storage like battery storage or if you have any voltage regulator then this will bring some additional challenges in order to maintain this voltages or in order to control the voltages; similarly, this utilization of smart distribution network by developing this different mode of scheduling and transfer schemes. In fact, this, I will discuss in my last module this you know bring some more challenges in formulating this distribution network reconfiguration problem ok. So, for this studying this reconfiguration problem one needs to search the papers available in the literature and you will simply search to get many papers available.

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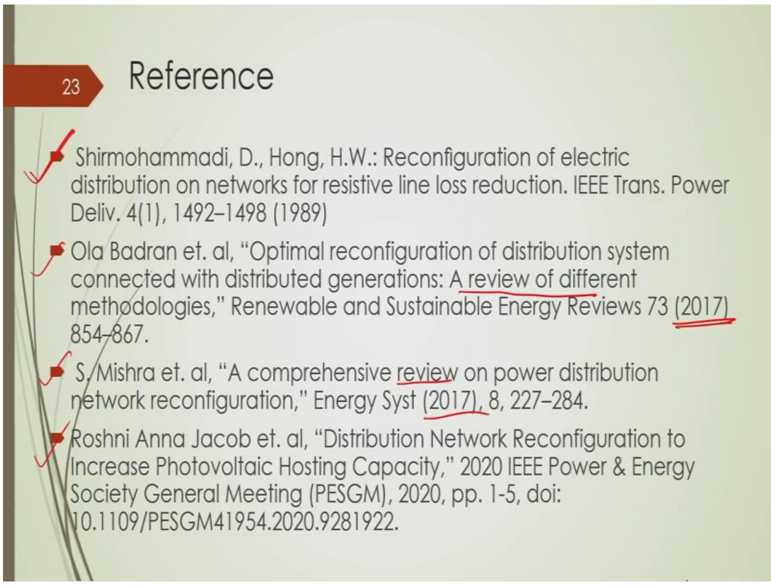

But form this part of the lecture, I sincerely acknowledge those four papers. One is very old one where you can see the first very early stage of reconfiguration approach is given. Another is a kind of review paper which is published in 2017. Another is also review paper published was published in 2017. So, one gets number of papers on this particular aspect, particular approach and one needs to have a thorough study of the available approaches before initiating the research in this particular field ok. So, with this I will stop this module that is module 6.

Thank you very much for attending this lecture.