IWAIS XI, Montréal, June 2005

On-Load Network De-icer for HV Transmission Lines

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***Abstract*—This paper introduces a new concept, the on-load network de-icer (ONDI), for de-icing HV transmission lines. The simplest implementation of the ONDI concept makes use of a phase-shifting transformer (PST) to induce very large AC currents to heat line conductors by the Joule effect. A single ONDI can handle a number of lines of different lengths without any need to transfer loads to other lines nor disconnect them. In the study presented, more than 900 km of 230- and 315-kV HV circuits can be de-iced with one ONDI installed in a strategically located substation. To put the ONDI to work, only existing circuit breakers need to be operated; no open air (ice-sensitive) disconnecting switches are involved. The on-load tap-changer of the PST provides a flexible control of the de-icing current. Using only conventional technologies, the ONDI is proposed as a natural in-house solution to both power system operators and maintenance people.**

I. NOMENCLATURE

On-load network de-icer, phase-shifting transformer, assisted phase-shifting transformer, transmission line de-icing.

II. INTRODUCTION

FOLLOWING a severe ice storm in 1998, Hydro-Québec decided to improve its network in order that, should such an event occur again, the impact on the population would be minimized [1]. Since then, many methods and devices for securing the network before during and after ice-storms have been investigated [2][3] but so far only a limited number of solutions are considered to be effective for removing ice accretion from transmission line conductors. One of the most common and widely used techniques consists in using Joule heating of the conductors by means of either DC or AC currents.

While DC current circulation is simple in principle, it requires first to disconnect the circuit to be de-iced from the network then connect a controllable DC source for feeding the appropriate heating current. A number of items of ancillary equipment also have to be added to the network at line terminals.

As for AC current circulation, although the current is the same as that of the network, it also requires disconnecting the circuit to be de-iced from the network. This is true, at least, for the short-circuit method (connection of a line to a source with the other end shorted), the opposed connection of phases method (connection of a line to two unlike phases at each end) and the synphase method (connection of a line to two different network voltages at each end) [4]. Although the combined use of these three AC techniques seems to allow de-icing of transmission lines over a wide range of line lengths, the fact remains that loads must be transferred and that a considerable amount of switching apparatus has to be put in place should a large network need to be protected from ice accretion. The object of this paper is to complement these line-dedicated AC techniques with a network approach to de-icing.

The paper presents a new concept, the on-load network de-icer (ONDI), for de-icing transmission lines. Its main characteristics are:

- Long range of action: in the present case over 900 km of 230- and 315-kV HV circuits can be de-iced with a single device;
- Flexible adjustment of de-icing current whatever the line length;
- Pre-heating of conductors possible before and during ice-storms to prevent ice accumulation;
- No withdrawal of HV circuit for de-icing;
- No transfer or interruption of loads during de-icing;
- Only existing circuit breakers switched to configure the network for de-icing (no ice-sensitive disconnecting switches);
- Only conventional technology, familiar to both power system operators and maintenance people, used.

The ONDI concept has been developed by CITEQ (a joint venture between HQ and ABB) in collaboration with TransÉnergie [5]. It is based entirely on the use of power flow controllers such as phase-shifting transformers (PST) [6][7] or assisted phase-shifting transformers (APST) [8]. In this respect, the ONDI can be seen as a generalization of the aforementioned opposed connection of phases method.

We show in this paper that the ONDI is suitable for de-icing HV circuits having of two-conductor phase bundles such as those used at 315 kV. However, it is not expected that it could be used for phases made of bundles of three or four conductors since the ratings of the ONDI would become excessive. Other technologies such as DC current de-icing or the concept of switching modules of bundled subconductors [9] seem more appropriate in such cases.

III. AC CURRENT CIRCULATION USING PHASE-SHIFTING TRANSFORMER

A. Imposing an AC current for de-icing

Fig. 1 shows how to use a phase-shifting transformer (PST) to create an AC current loop in transmission lines. To illustrate the concept, two ideal transmission lines are connected between a generator and an infinite network. A PST is connected in series with one of the two lines. Per units are used.

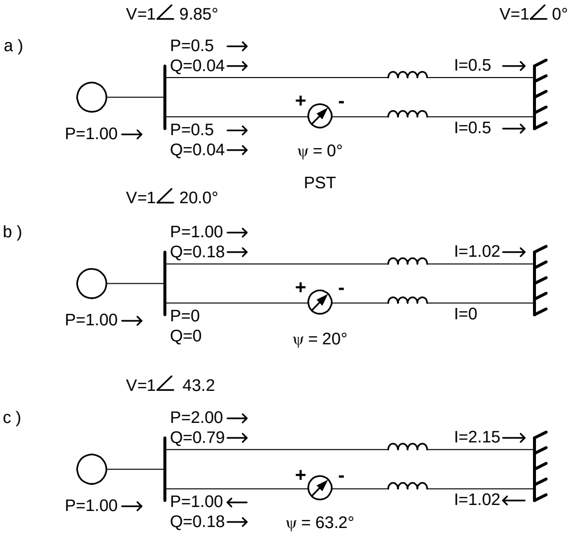

Fig. 1. Controlling a large AC de-icing current with a phase-shifting transformer.

When the phase-shift ψ across the PST is zero (Fig. 1a), the current flowing from the generator to the infinite network is shared equally by the two lines. However, a 20° phase-shift (Fig. 1b) forces all the current to flow in the upper line only. As can be seen, the unloaded line carries zero current, since the phase angle at its terminals is reduced to nil by the PST. The current of the loaded line is therefore doubled. Applying a 63.2° phase-shift at the PST terminals (Fig. 1c) allows the current in the upper line to be increased by a factor of four. Our study shows that such an increase in the line current is more than sufficient for de-icing a transmission line equipped with phases comprising two bundled conductors.

It is important to underline the fact that a PST creates a circulation of real power in the lower line that is opposite in sign to that in the upper line. The increase in the current of the loaded line is not related to a circulation of reactive power. Besides, the large de-icing current in the upper line is the sum of the load and the PST currents. Hence, the more load current available, the smaller the rating of the PST can be. Load current is used whenever possible to reduce the PST size and cost.

In real situations, the lines to be de-iced are connected to a complex network comprising other lines, loads and power generators. Although this makes the planning studies complex, operation of the ONDI can remain simple if well planned.

B. Phase-shifting transformer

A PST is a special type of three-phase transformer used for controlling power flows in transmission lines. This technology, commercially introduced in the 1940s, is rarely needed in power systems and remains uncommon. Only about 100 units are presently in service in North America.

Fig. 2 shows a simplified representation of a two-core PST, each core representing a distinct transformer. As explained above, a PST is typically connected in series with a transmission line. Hence, voltages V_s and V_r are those of the substation and the transmission line respectively. The series transformer has one of its windings split in two while the other winding is connected to the tap-changer of the shunt transformer, which is fed from the mid-point of the winding that is connected in series with the line.

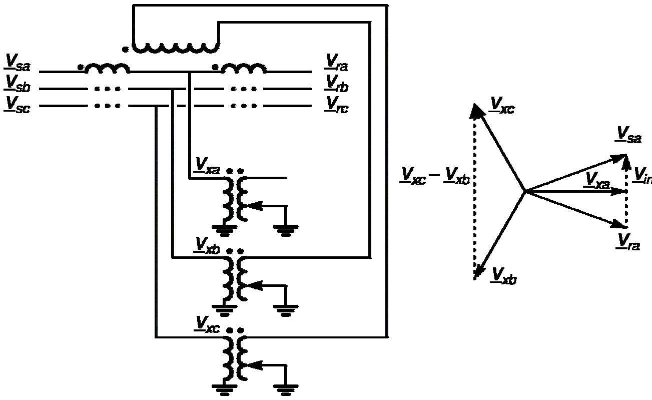

Fig. 2 Simplified representation of a PST suitabled for de-icing 315-kV lines.

When the tap changer of the shunt transformer is adjusted so that there is no voltage applied to the series transformer, V_s is equal to V_r and the PST has no impact on the power flow prevailing on the line. Moving the tap changer from that point imposes a voltage on the series windings that changes the phase-shift between V_s and V_r , as shown by the phasor diagram. In turn, this phase shift has a direct impact on the line power flow. Depending on the sign of the phase shift, the line power flow can be increased or decreased. The current flowing in the line also varies in accordance with this change in power flow. Thus a PST is a flexible means for increasing the current of a transmission line.

C. Voltage support

The current needed to de-ice a two-conductor bundle can be up to three times the current level that makes the line self-compensated and its voltage equal to 1 pu at any point. This implies that, in some cases, reactive power production has to be progressively put in place when the PST increases the line current from the nominal point up to the de-icing level. For instance, addition of voltage support has shown to be necessary only for de-icing the longest 315-kV line of Hydro-Québec's Matapedia network. The current level needed for de-icing its two bundled conductors cannot be reached without it. As for the 230-kV transmission lines, which use one conductor per phase, the current needed for de-icing is much lower and the network voltages remain acceptable using only existing equipment such as shunt capacitors.

One simple way of providing voltage support is to add series compensation to the transmission line: the higher the current forced by the PST, the higher the reactive power generated by the series capacitor. As observed in the Matapedia application study, this provides a voltage support that adjusts to the needs of the network.

Addition of a capacitor across the PST terminals is another way of providing a self-adjusted voltage support. However, the resulting assisted phase-shifting transformer (APST) can create overvoltages if line disruption occurs during de-icing. Proper selection of the capacitor can minimize this phenomenon but uncertainties related to insulator flashover under iced conditions favor the series compensation approach.

IV. MATAPEDIA APPLICATION STUDY

A. *Matapedia Network*

The Matapedia network shown in Figs. 5 and 6 is part of the HQ power system. It serves the Gaspé Peninsula, a large 450-km by 150-km territory located in the eastern reaches of the province of Québec, on the south shore of the St. Lawrence River.

One of the scenarios considered for providing a secure electricity supply across this region consists in de-icing a total of seven transmission lines, two double-circuit 315-kV lines and five single-circuit 230-kV lines, totaling 918 km of HV circuits. Of interest for the study presented here is the fact that up to 1000 MW of wind turbines are to be installed on the Matapedia network. As a consequence of this new generation, addition of series compensation is considered as a means of improving the 315-kV system.

Prior to an ice storm, residential and industrial loads are typically around 70% and 100% of the annual maximum. Under a severe ice-storm of some 60-km by 40-km, it is estimated that only part of the large Gaspé Peninsula would be hit, resulting in a reduction of the total load since many distribution lines could collapse. Moreover, ice-storms are susceptible to occur while residential loads on the network are relatively low. Hence, to be on the safe side, minimum loading conditions following an ice storm were assumed to be 35% and 70% for residential and industrial loads respectively. As for the wind turbine generation, it was considered that it could be anywhere between zero and 100 percent.

B. *Climatic Constraints*

This study uses the climatic conditions prevailing during the 1998 ice-storm. Fig. 3 shows the winds and temperatures registered every hour at Dorval, near Montréal, during the five days of this event. The maximum rate of ice accumulation reached 1 mm/h without exceeding 20 mm over a 24-h period.

It must be pointed out that the weather conditions estimated here for the purpose of this preliminary study are not final. Some Work remains to be done before drawing conclusions about the climatic constraints as numbers are expected to change slightly once they have been revised to take into account the specific characteristics of the Gaspé Peninsula.

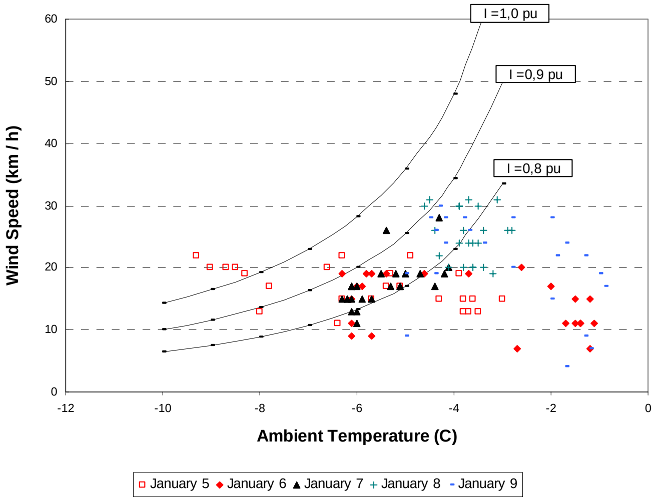

Fig. 3 Use of the weather conditions recorded during the 1998 ice-storm for selecting de-icing current of a transmission line.

C. *Operating Constraints*

As planned here, the ONDI is strategically installed at Rimouski substation, which is the main substation in the Matapedia network. From there, it is possible to de-ice the most important transmission lines in sequence.

In the case of an ice-storm located around Rimouski substation, the ONDI has to de-ice 782 km of HV circuit connected to it and running across an ellipsoidal area of 160 km by 130 km. This is the most demanding condition that the Matapedia network has to meet. Assuming an ice accumulation of 1 mm/h and taking into account the time needed to sequentially connect and de-ice each circuit, it turns out that the ONDI must be designed to remove 10 mm of ice in 1 h or less and that the de-icing schedule for all the lines must be completed within 10 h.

It must be pointed out that, although these constraints are summarized in just a few words, establishing them has required an enormous amount of work since different network configurations are possible during de-icing, while great variations of both loading and wind turbine generation must be taken into account.

D. *Specification of De-icing Currents*

The current levels needed for de-icing the lines have to be determined for each circuit individually, taking into account their physical properties and the climatic conditions prevailing locally during ice-storms. These currents must be high enough to ensure proper de-icing without overheating the line themselves or any other existing equipment in series with them.

Following de-icing tests in IREQ's climatic chamber, TransÉnergie set up de-icing current guidelines for each type of conductor used on its power system. This data was superimposed to the weather records in Fig. 3. The curves yield the current needed for removing 10 mm of ice in 1 h from any given transmission line. In this generic figure, 1 pu represents a de-icing current that ranges from 700 to 1900 A, depending on the conductor characteristics.

It can be seen in Fig. 3 that the higher the de-icing current, the more often ice melting is possible and the more secure the current rating of the device installed for this purpose. Using such a tool, a planner can iteratively find the appropriate current needed for de-icing each line taking into account the following factors:

- required security level of the electricity supply;
- expected weather conditions of a severe ice-storm;
- mechanical strength of towers;
- current capability of all the apparatus subjected to the de-icing current such as circuit breakers, disconnecting switches and transformers;
- operational aspects related to de-icing;
- ratings of the ONDI.

V. OPERATION OF AN ON-LOAD NETWORK DE-ICER

A. *Configuration of the network for de-icing*

As soon as an ice-storm is forecast, the very first step is to determine which line or lines will have to be de-iced. To do so, TransÉnergie's meteorologists analyze Environment Canada data and provide Operations Department personnel with maps showing expected ice accumulations. TransÉnergie's real-time ice monitoring network (SYGIVRE) also provides data on actual ice accumulations for the whole network. Maps are regularly updated and ONDI is planned to be energized 8 h before anticipated ice accumulations of 10 mm or more have started.

Whatever the ice-storm location, it is of prime importance that all feasible de-icing protocols be prepared in advance. Operators must be trained and equipped with all the documents needed to operate the ONDI. As shown below, the fact that a single device can de-ice many kilometers of HV circuit means that configuring the network for de-icing cannot be improvised. This is particularly true when the line to de-ice is not in the immediate vicinity of the substation.

With regard to operator training, this is expected to be facilitated with the concept disclosed here, since the ONDI does not require any loads to be shut down during de-icing. Training is therefore possible over the whole year.

B. *Energization of the ONDI*

The ONDI can be energized without disrupting the network. As shown in Fig. 4a), circuit breakers CB1 and CB2 are initially closed while the PST circuit breakers are open.

To de-ice the line indicated, the ONDI is set at zero-phase shift and its circuit breakers are closed. Then circuit breakers CB1 and CB2 are opened. Thus, as can be seen in Fig. 4b, the ONDI falls in series with the other line, which was depicted in Fig. 1. As shown, lines remain in service during de-icing, thus preserving network integrity at all times.

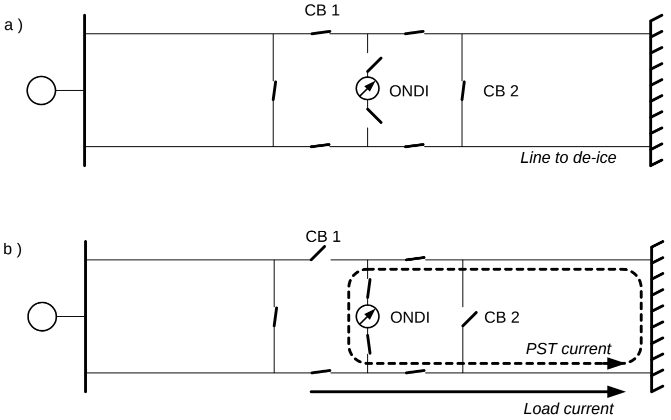

Fig. 4 ONDI energization and network configuration for de-icing.

The ONDI is now ready to induce a current that will add to the load current and make up for the de-icing current. Watching the current meters, the operator can move the tap-changer position up to the point where the current needed for this specific line is reached.

C. *De-icing of a 130 km long 315-kV line*

The ONDI has to de-ice two 315-kV double-circuit transmission lines. The first double circuit, 100 km long, is numbered 3082/3083 on Fig. 5. The other is 130 km long and numbered 3089/3090. Although not shown here, series compensation for these four lines and wind turbine generators were included in our study. Hence, the PST with its two series circuit breakers are the only additions needed to implement the ONDI concept. Integration of the ONDI in the substation is similar to that of a conventional transformer. As for line protection requirements, relay settings of the 315-kV line to de-ice will have to be changed for taking into account the addition of the PST.

Fig. 5 shows that only six circuit breakers, including those of the ONDI, need to be switched for configuring the network for de-icing line 3090 adequately. No other switches such as disconnecting switches need to be opened or closed. As explained in Fig. 4, the load current and the ONDI current, shown by the dotted line, are combined to heat the line by the Joule effect and remove 10 mm of ice in less than 1 h. The highest de-icing current that can be obtained for this line in our study reaches its thermal limit at 2400 A, which is approximately 3.8 times the nominal current that provides a flat voltage profile along the line. At this current level, de-icing should last less than half an hour.

Once de-icing is completed, the ONDI current is reduced to zero, the network is reconfigured in a similar manner to that shown here and the ONDI current is increased again for de-icing line 3089.

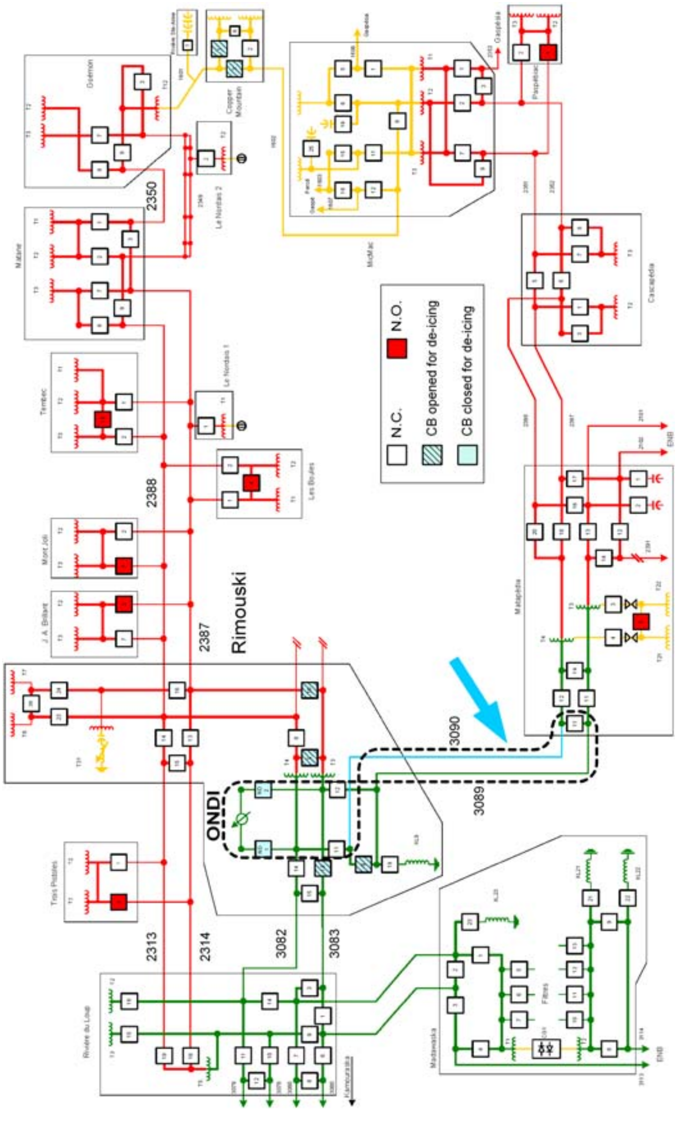

Fig. 5 De-icing of the 130 km long 315 kV transmission line 3090.

D. De-icing of a remote 230-kV line

The five 230-kV single-circuit transmission lines to be de-iced are 2313, 2314, 2387, 2388 and 2350, all of which are 100 km long except 2350, which is 70 km.

Fig. 6 shows that a total of 15 circuit breakers need to be switched for adequately configuring the network and de-icing the remote line 2350. It is worth emphasizing the fact that here the ONDI is capable of de-icing a 70-km line whose nearest extremity is 100 km away. The dotted line shows the rather complex path of the current induced by the ONDI. This clearly illustrates the necessity for thorough planning studies in order to identify all the optimal network configurations to use.

De-icing of the other 230-kV lines can be performed in a similar manner. Although not shown here, our preliminary study indicated that the Matapedia network can be configured to simultaneously de-ice line 2313 with the first 60 km of line 2388 or line 2314 with the first 60 km of line 2387. In both cases, a total of 160 km of line can be de-iced at one time.

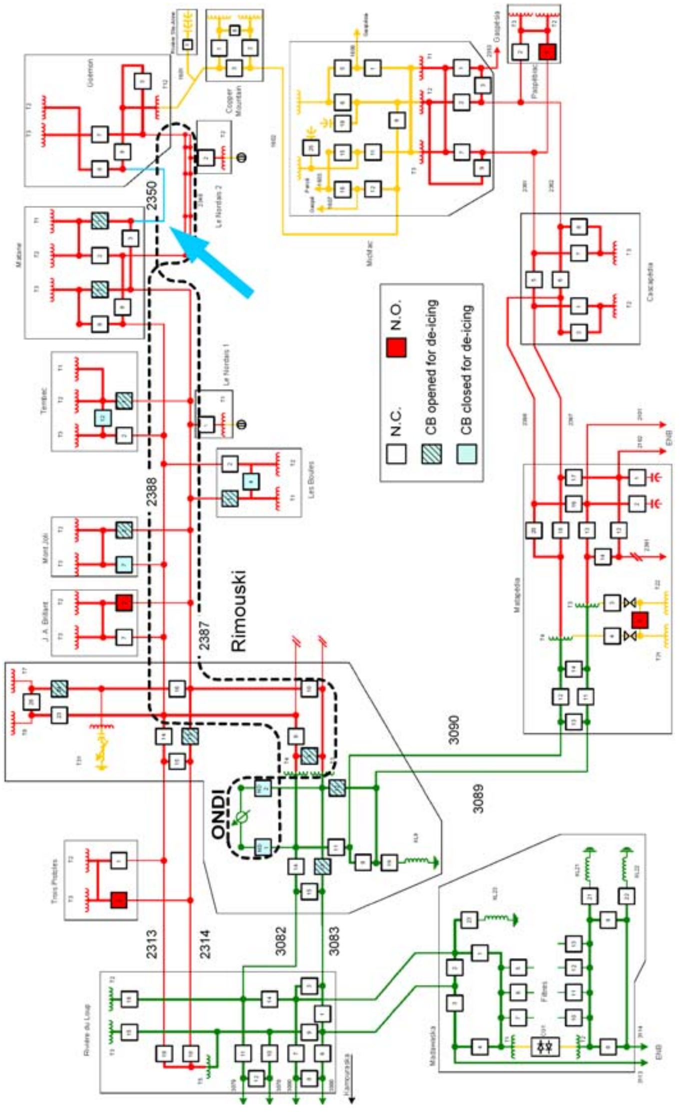

Fig. 6 De-icing of the remote 230 kV transmission line 2350.

E. Pre-heating a transmission line prior to ice accumulation

Since the ONDI can de-ice transmission lines with all loads in service, it can also be put in place to heat a HV circuit well in advance of a predictedly severe ice storm. This is advantageous for preventing ice accumulation on any line.

Furthermore, tests in IREQ's climatic chamber have shown that the currents needed for preventing ice accumulation are significantly lower than those for de-icing. For this reason, prevention of ice accumulation is less demanding on the network.

F. Voltage regulation during de-icing

Under all de-icing conditions and during the whole process of increasing and decreasing de-icing currents, network voltages remain within the emergency specifications of ±0.1 pu. As a matter of fact, in most cases, voltage regulation is even better, as the nominal operating range of ±0.05 pu can be met. To achieve such a satisfactory voltage regulation, existing shunt banks are operated in some instances.

G. Ratings of the PST

The rating of the PST at 315 kV and -5°C is 920 MVA, which translates to around 700 MVA at 30°C, the temperature generally used to specify ratings. This allows a 1700-A current to be added to the existing load currents in 315-kV circuits. As for the required phase-angle ranges, the PST must be able to cover –50° to 0° and 0° to +50° without interruption.

To meet these requirements, the PST will probably need to be slightly more complex than shown in Fig. 2. For a large phase-shift such as ±50° it might be necessary to add an auxiliary winding to the shunt transformer and connect it in series with the tapped winding. The auxiliary winding would then be used to displace the ±25° phase angle range provided by tap changing by some –25° or +25° to achieve the overall ±50° needed.

VI. FURTHER STUDIES

As far as planning studies are concerned, the concept presented here has been thoroughly validated. However, considerable work remains to be done to ensure that the ONDI provides full security under all abnormal events. In particular, extended transient studies of the EMTP type are required to investigate the global behavior of the ONDI and series compensation. Regarding this aspect, two 500-kV, 650-MVA, ±25° PSTs were commissioned in 1998 on the Salt River Project network (AZ) to increase the power flow of a 70% series-compensated transmission line [10]. Although the ONDI phase angle range is significantly larger than that of these two existing PSTs, its voltage level is much lower, which makes this implementation a good indication that the ONDI concept is sound and worth pursuing.

VII. CONCLUSIONS

On the basis of the Matapedia network, the on-load network de-icer (ONDI) study presented here has shown that:

- Making innovative use of a PST allows de-icing over 900 km of 230- and 315-kV HV circuits;
- Joule effect de-icing of two bundled conductors by means of AC current can be achieved while maintaining voltages in the network within emergency limits;
- Residential and industrial load supply can therefore be maintained without any interruption during de-icing;
- Circuits can be heated before and during ice-storms to prevent ice accumulation;
- Only existing circuit breakers need to be switched to configure the network for de-icing (no ice-sensitive disconnecting switches);
- The technologies used are conventional and familiar to operators and maintenance people.

Although the PST has a high rating, it is expected that the ONDI concept shall compare very well with mechanical reinforcement of more than 900 km of HV circuits or with many other means of de-icing.

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