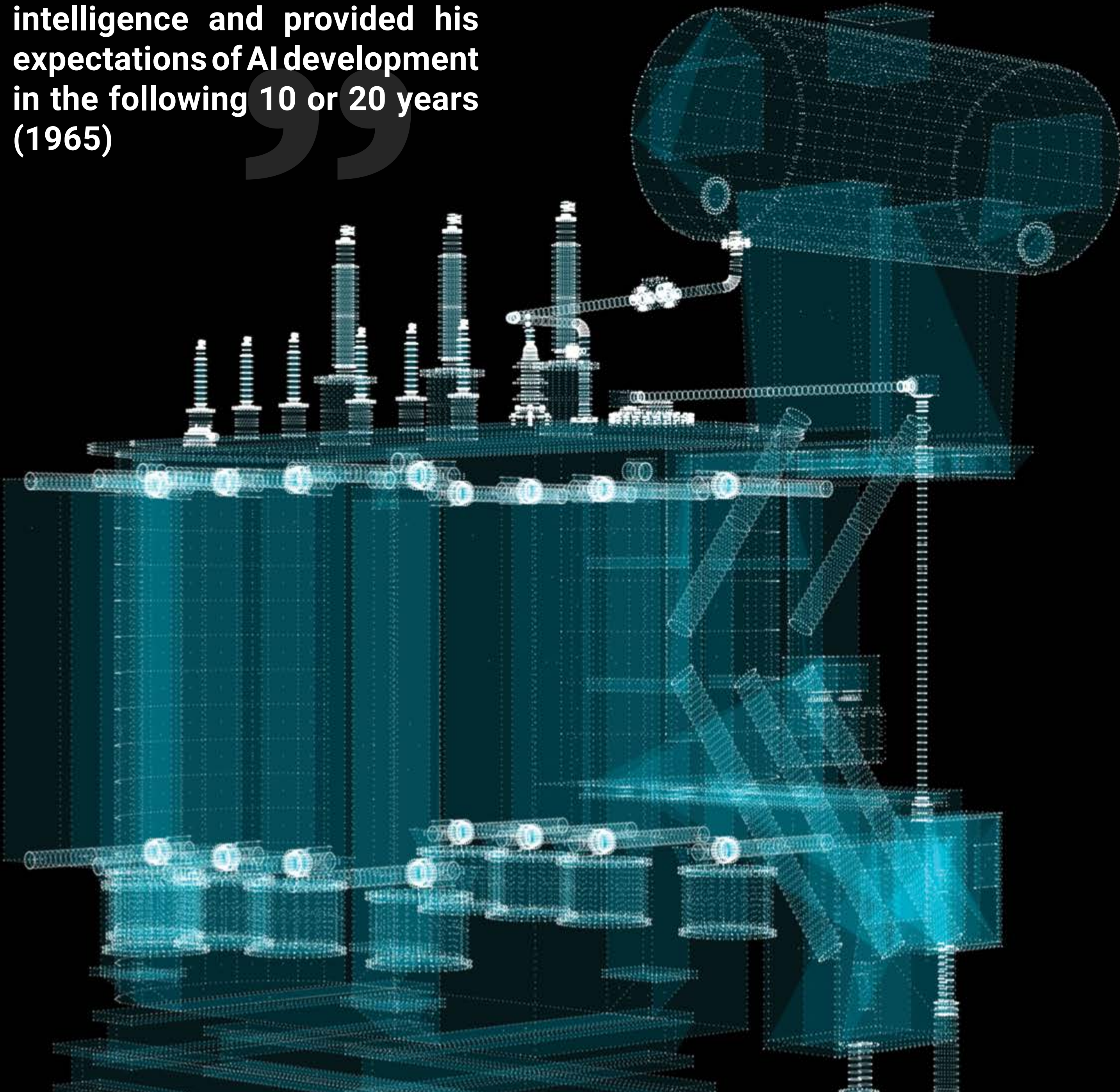
Herbert Simon was one of the founding fathers of artificial intelligence and provided his expectations of AI development in the following 10 or 20 years (1965)



ABSTRACT

Artificial intelligence (AI) attempts to be involved in power transformer diagnostics are relatively old and coincide with the AI development in close domains. Artificial intelligence concept and implementation is still an emerging technology, even though the impression is that AI is ever-present. In medicine and diagnostic fields, AI has faced many challenges, and most of them are probably impossible to overcome, even by the most powerful computers.

Transformer oil diagnoses and health index techniques mainly based on DGA, as well as oil tests, are some quite attractive techniques for the vital electrical industry, and they seem to be adaptable to artificial intelligence. Moreover, the combination of AI and transformer diagnosis also became attractive in the last couple of decades due to the diminishing number of human experts in this field.

KEYWORDS:

artificial intelligence, challenges, DGA, power transformers, testing

Marius GRISARU

In the power transformer industry, AI may be very helpful in describing potential opportunities and resolving technical issues

Artificial intelligence challenges for power transformer maintenance

Introduction

The artificial intelligence concept is an antique one. The algorithm was developed by a great scientist of the ancient world, the 9th-century Persian mathematician Muhammad ibn Mūsā al-Khwārizmī. Of course, the word algorithm itself is derived from his name. Certainly, in modern times, it was first introduced by Alan Turing in his Enigma and Imitation Game. The modern software technique was developed in 1955 by John McCarthy in the famous Dartmouth summer research project on artificial intelligence. The Nobel prize was awarded a few years after that to Herbert Simon for the development of such software. Computer scientists expected that in 10 or 20 years from then, a brain or machine would already be similar to human brains in a majority of aspects.

Muammad ibn Mūsā al-Khwārizmī

Herbert Simon was one of the founding fathers of artificial intelligence and provided his expectations of AI development in the following 10 or 20 years. He understood the future of machines and the utmost importance of computers. By 1965, Simon was certain that "machines will be capable of doing any work a man can do." His visionary perspective on decision-making processes, climate change, and flaws in economic theories prove to be even more relevant and crucial in the 21st century. But Simon's vision still needs to be extended even after 60 years after his first prediction.

Since then, we have faced an increase in the fields and applications for AI and ML. AI software play chess and even may win against human players, successfully filters spam in our mailboxes, and many other simple routine assignments. Although AI has been planned to be applied in many fields, such as self-driven cars or medicine, AI software is not yet capable of replacing drivers (Palade at al., 2022) or medical doctors (Koteluk, Oliwia et al., 2021). From those papers relating ML, AI and deep learning concepts, as well as from daily life in our modern society, we have realized the main obstacles to the introduction of all software-associated intelligence for more important decisions. Those barriers arrive from different fields, such as philosophy in the case of autonomous cars, with the query, "Should autonomous cars sacrifice you to save a child or a dog?" (Etienne, Hubert, 2022).

Herbert Simon - nobelprize.org

Medicine is even much more complicated since it also involves ethics. Very few people allow free access to their medical files, and this imposes difficulties in having a proper variety of cases from which the ML and AI may be trained. The first fields of medicine in which AI was tried were radiology and oncology, by application of image analysis that may be superior to the diagnostic capability of a human. The main technical issue that ML needs to overcome is the number of potential manipulations of input data that can influence the system's decisions. For example, a simple action such as adding a few extra pixels or rotating the image can lead to misdiagnosing and cancer misclassification as malignant or benign (Koteluk, Oliwia, et al. 2021).

Transformers are one of the most vulnerable targets in cyber attacks, and by attacking and disturbing their operation, it is quite easy to deregulate everyday life with blackouts and industrial damage

In the power transformer industry, AI may be very helpful (Yazdani-Asrami, Mohammad, et al., 2021) in describing potential opportunities and solutions that artificial intelligence (AI) techniques and approaches can offer for resolving technical issues related to superconducting transformers: from design to troubleshooting.

Attempts to use artificial intelligence for power transformer maintenance are almost as old as AI. Baroni et al. in 1970, Lowe 1985, and (Wang, 2000) are only a few examples of early literature.

In our millennium, the number of papers and literature on the attempts to take advantage of new programming concepts and develop a more sophisticated approach to transformer diagnosis has only increased, probably exponentially. This trend is driven by several actual facts, both positive ones and those less desired: developments in hardware and software related to artificial intelligence and automated monitoring and, on the other side, the diminution of transformer maintenance experts, especially in the oil and DGA domain. The programming development is, of course, a positive fact, but the reduction of DGA chemical experts is probably less desired than it has been the reality in the last two decades, and the reasons for this fact may be a subject for another column.

In this column, a few obstacles are highlighted together with some difficulties that will probably delay or even prevent the full implementation of AI, ML, and deep learning for transformer maintenance, especially by Dissolved gas analysis.

Other oil tests besides DGA are relatively less suitable for a single diagnosis and may appear only in a complete health index evaluation with all other parameters. As stated, everywhere, it is rarely customary to take any action on single oil tests besides the DGA one. DGA is highly recommended to assess transformer conditions in conjunction with other chemical or non-chemical tests that may support critical decisions. But for DGA is not compulsory as for any other oil test existent today in guide standards such as IEC60422.

This column is not deal with an organized database of the data accumulated by a single or transformer fleet and uses simple algorithms that imitate the calculation of desired diagnostic methods, such as ratios and graphic methods from all the types. Those programs are definitely useful and assist transform oil experts in seeing the whole picture faster and more accurately. Even though there are few approaches to developing such databases and calculating algorithms, some expertise is needed to develop an easier and clearer picture. Such programs may be acquired both from well-established and quite new developers, and it is a matter of ability to evaluate such software. Of course, anyone may develop this simple code in most types of available programming code. I myself develop such algorithms in Excel with basic programming knowledge and invite all the readers to try doing it by themself.

The appearance and abundance of online DGA and moisture in oil online devices impose a real need to accumulate, store, and reliably process all big data available from those devices. Of course, humans cannot type all those data from online DGA devices. Such big data requirements of data scientists to use data analytics software, visualization tools, and of course, manipulate the data that possess correlations to equipment conditions. Multiple DGA data have three great advantages for being a model subject for AI technology:

1. DGA diagnosis already has multiple (more than 60) models for deducing transformer conditions from DGA single or multiple entries data.
2. DGA is recognized as the single most important test for power transformer life assessment.
3. A successful DGA diagnosis can save precious equipment together with the organization's reputation and capital.

Challenges of AI application in DGA and oil tests

Transformers and data security, cyber attacks

This is probably the most serious difficulty to overcome before making any decision on the digitalization of online and even offline transformer test results. Even though the actual hostilities occurring at the time this column has been written are happening in the physical world, most of the international conflicts today are fought within the cyber domain. Transformers are one of the most vulnerable points of this virtual war, and by attacking and disturbing their operation, it is quite easy to deregulate everyday life with blackouts and industrial damage. The more transformers are digitalized and connected to cloud software, the more the electrical industry is vulnerable to cyber-attacks. These facts are mentioned in professional literature such as Ahn et al., 2021 IEEE, and daily papers like Forbes. They and other media cite the for-

Uncertainty sources and magnitude of 3 DGA methods

Error source	Inaccuracies %					
	DGA offline		DGA portable		DGA online	
	low	high	low	high	low	high
Sampling	10	25	5	15	0	30
Oil transportation	5	15	0	10	0	10
Measurement	10	30	15	40	15	30
Diagnosis	0	25	15	30	15	30
Overall inaccuracy	**25**	**95**	**35**	**95**	**30**	**100**

Figure 1. DGA data overall uncertainty

Figure 2. Data sharing

mer US president Donald Trump saying that he "directed utilities not to purchase bulk power systems from 'adversaries'". President Joe Biden also makes cybersecurity a priority. In this context, it is easy to realize what may happen if the online DGA is hacked and transmits alarms to de-energize the transformer. Relying on offline oil and DGA tests from an internal lab without being visible on any cloud media may avoid such a situation. Also, relying on the software located outside the transformer owner's organization may lead to intentional irregularities and invite cyber-attacks. Transformers Magazine wrote an interesting piece on this issue on 6 July 2020.

Ambiguities in DGA diagnosis

DGA is not pure science. IEEE C57.104 2019 defines DGA as more of an art. "DGA is more of an art than a science". Other scholars and commercial organizations consider DGA a statistics data science, but data science is itself a data manipulation art.

The sources of uncertainties in DGA diagnosis are many, as shown in Fig. 1. Unfortunately, these are conservative estimations, and real figures may be even higher, e.g., reveal a lower accuracy. The reasons for such uncertainties are debated in previous columns and in the Transformers Academy's DGA course. All software, from simple algorithms to deep learning, should take into consideration the actual level of overall accuracy for the figures, and this data is regularly undetermined. A human scientist that indeed refers to DGA as an art, may have the chance actually to evaluate those causes, but Artificial Intelligence software is still not capable of doing so since, for that, it should have access to all those fine and less-considered parameters.

For being able to perform an accurate estimation, the actual data should be shared, and opinions need to be peer-discussed by colleagues

Data sharing

For being able to perform an accurate estimation, the actual data should be shared, and opinions need to be peer-discussed by colleagues. The more frequently this process occurs, the more ability and value such an expert will be more valuable.

Power transformer diagnosis is a dynamic, rapidly developing science. Requirements for the design, materials, testing capabilities and diagnostic approach have, over the years, led to the need for a different approach to transformer diagnosis. For a new concept to appear updated in any type of software, it needs to pass through six phases:

1. A phenomenon is discovered in a laboratory or during an actual test in the field.
2. Discussion among peers.
3. Publication in specialized qualified media such as Transformers Magazine.
4. Presentations at various working

Same as a human expert, also AI software performance highly depends on the size and variety of data bank tests and transformer characteristics

groups such as CIGRE, IEC, IEEE, ASTM, and international conferences.
5. Acceptance by the industry to appear in revised standards or new standards.
6. Finally, adoption and implementation in software as an algorithm or AI and accepted as current technology.

These six stages usually take at least 10 years or even more. For instance, biodegradable oil such as natural or synthetic esters appeared on the market 30 years ago and only now the standards for their maintenance and DGA diagnosis are being developed. It will probably take at least 5 years for the development of an adequate AI diagnosis for a DGA diagnosis of non-mineral power transformer oils. Until then, new insulating liquid types may challenge the industry, such as nano-based ones.

This huge delay makes the majority of existing AI software questionable in its relevancy to the modern power transformer.

Expertise and data training

A true artificial intelligence approach requires continuous feedback and training, as presented in Fig. 5.

The sources of AI training for DGA power transformer diagnosis originate from:

1. Human experience experts are willing to distribute their knowledge and experience. The motivation for AI development of human experts reduction is also a barrier to developing a quality AI approach for DGA. If this trend continues, this important training type may limit AI performance regardless of the computing power
2. Data bank availability. Same as a human expert, also AI software performance highly depends on the size and variety of data bank tests and transformer characteristics. Those data banks should be classified with as many more individual details as possible, should contain all types of age, size, design, exploitations, and particularities to existing power transformer technologies, and data should be filtered adequately. Those are only a part of the considerations for composing and possessing a valuable database. When a new study is initiated by a standardization organization or research institute, the first step is to collect as much data as possible, especially for DGA diagnosis. To be able to convince organizations to share such data, a data anonymization process is required, which of course, may affect the final conclusions. Those data banks are almost impossible to be accumulated by commercial or even institutional organizations. On

Figure 3. Post-mortem inspection - the compulsory stage for successful transformer health assessment and for AI

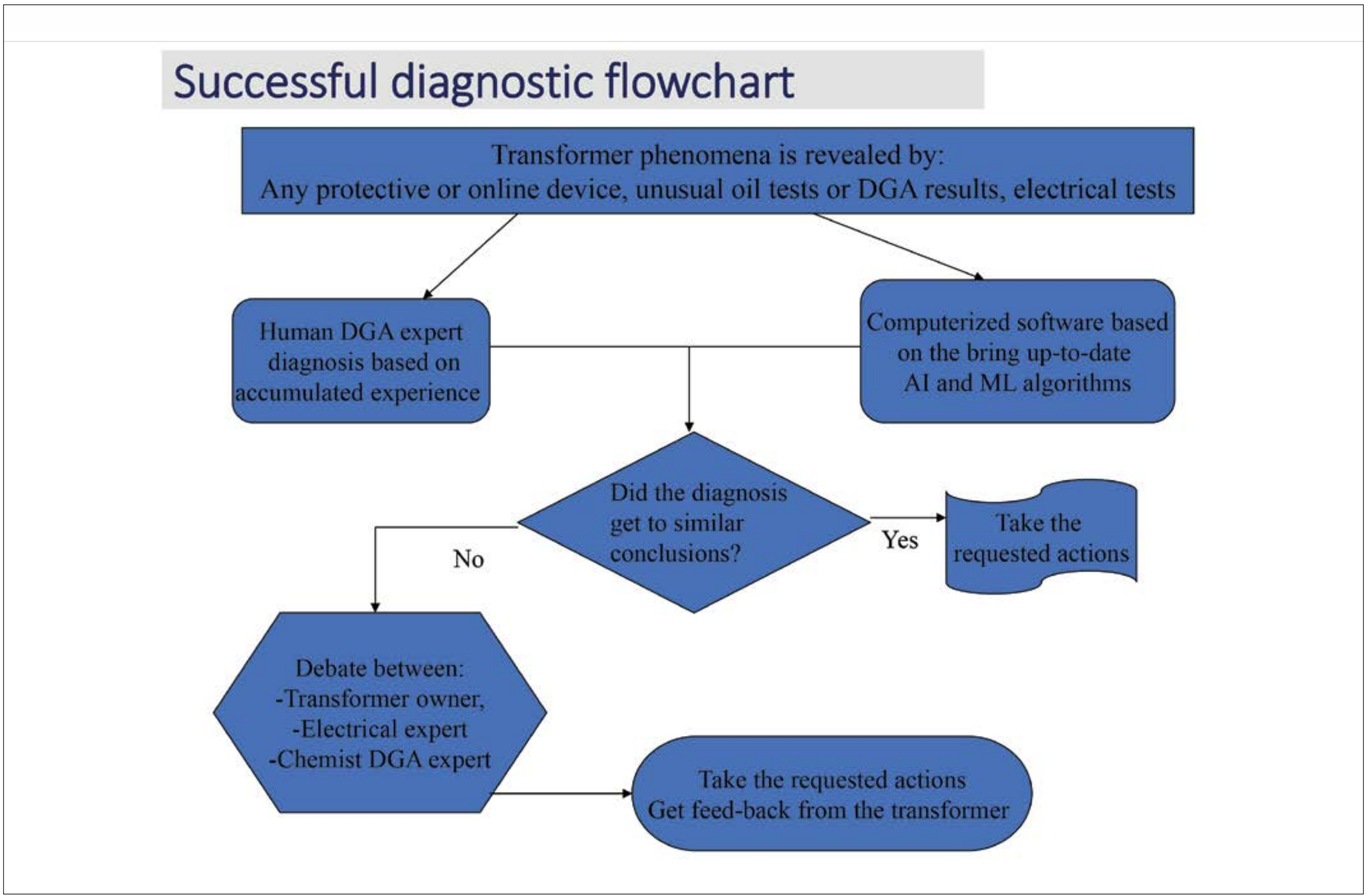


Figure 4. DGA diagnostics flowchart

the contrary, a human expert may be exposed much more easily to relevant data banks during change opinion and by having access to technical literature. Here is important to emphasize that a large part of valuable technical papers are not open access and even not through academic source. Some organizations restrict the availability of their accumulated data only to non-competitive industries.

3. As occurred recently, different organizations published unbiased and problematic conclusions based on the unbalanced database. These undesired phenomena happen due to restricted access to data banks from several users only.
4. Companies generally avoid sharing their data because of security reasons and commercial reasons. Without those databanks, the chance of any AI being correct is not high. Humans as well need to base their conclusion on limited cases.
5. **Post mortem inspection.** Fig. 3. One of the main contributors to the quality DGA and transformer diagnosis is online and real feedback on the previous recommendation. A human expert may provide reliable recommendations only after numerous internal inspections or after recommendations or post-mortem. The human expert needs eventually to be able to enter inside the transformer tank or to inspect the active part immediately after de-tanking. The same consideration should be applicable also to AI and any software. This is the same case as in medicine; young doctors should be exposed to the operations and post-mortem analysis of patients. For the transformer, this stage is even much more critical because the transformer's technology and materials are changed much more rapidly than for living beings.

A successful AI requires continuous updating to the most recent technology developments in the relevant chemistry, electrical, mathematics, and engineering domain

Fig. 4 shows a proposed flowchart for having a successful integration of human and AI expertise. The chart offers a balanced opinion exchange between human experts. After each stage, feedback to both experts (human and computer) is desirable.

Conclusion

Artificial intelligence is a powerful tool for performing routine tasks and taking interpolated actions. Humans' task is to train sophisticated algorithms properly and correctly and provide continuous feedback and inputs to achieve a valuable expert system that will correctly diagnose transformer conditions. The lack of human experts is also a good motive to develop AI programs, but at the same time, it imposes difficulties in the implementation of valuable AI for transformer diagnosis. Because DGA procedures, from sampling to diagnosis, require soft skills and are less compared to an exact science, it is also problematic to translate them successfully into a code that may adequately express all the ambiguities associated with these techniques.

A successful AI requires continuous updating to the most recent technology developments in the relevant chemistry, electrical, mathematics, and engineering domain.

However, the storage and computing capacity of AI is far higher than humans, and AI may take an unemotional decision on continuous transformer maintenance. Almost certainly, AI has a neutral commercial bias and is less suspected of having any unrelated commercial interests in its diagnostic output.

From the perspective of 2022, it seems we are still waiting for those "next 10 or 20 years" to achieve an AI that may substitute human experts. Until then, It will require much more funds, efforts, research, and studies for any software to advance from a simple calculus procedure according to existent DGA diagnosis schemes. As for other domains, such as medicine or autonomous cars, as well as for DGA and transformer assessment, AI is still an early-emerging discipline.

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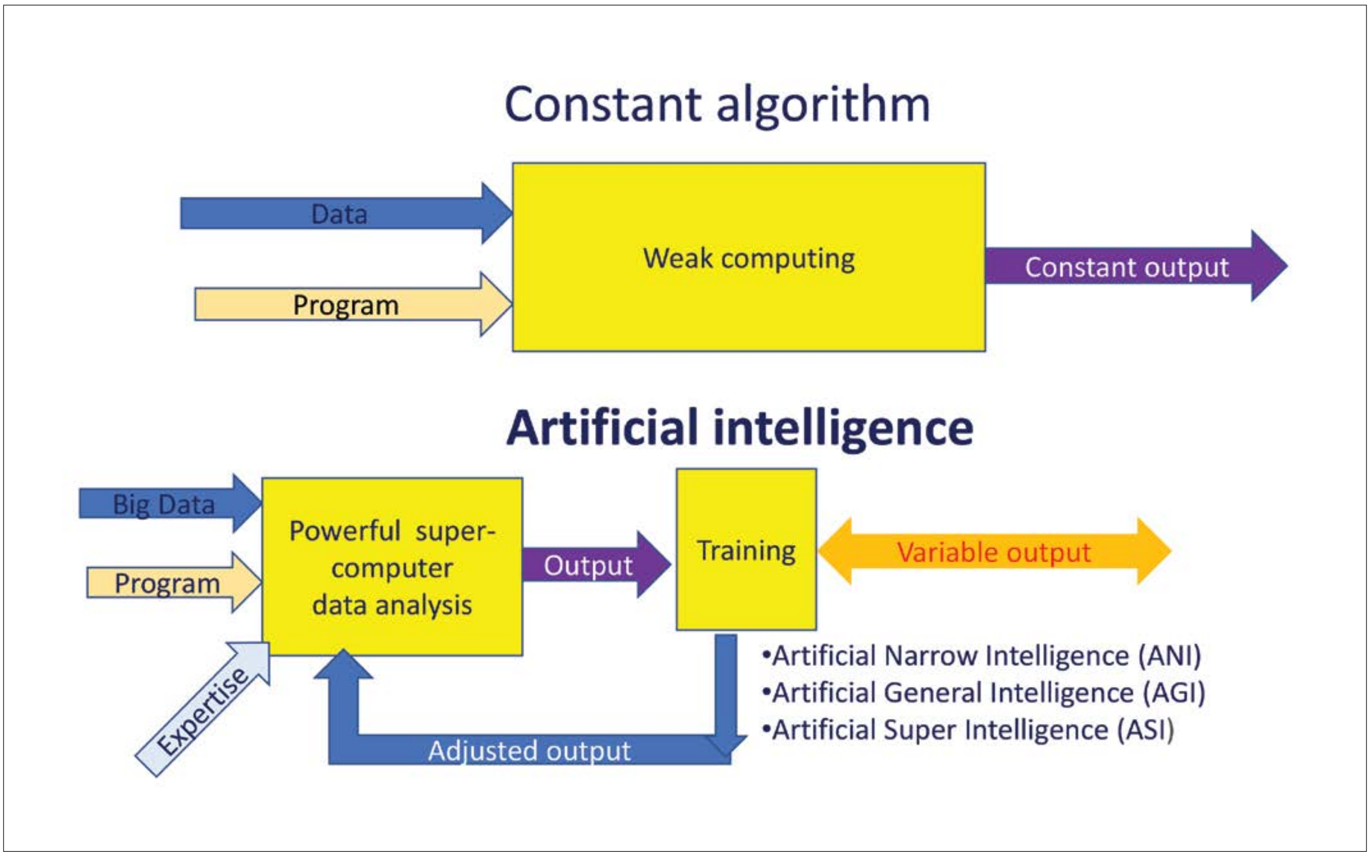
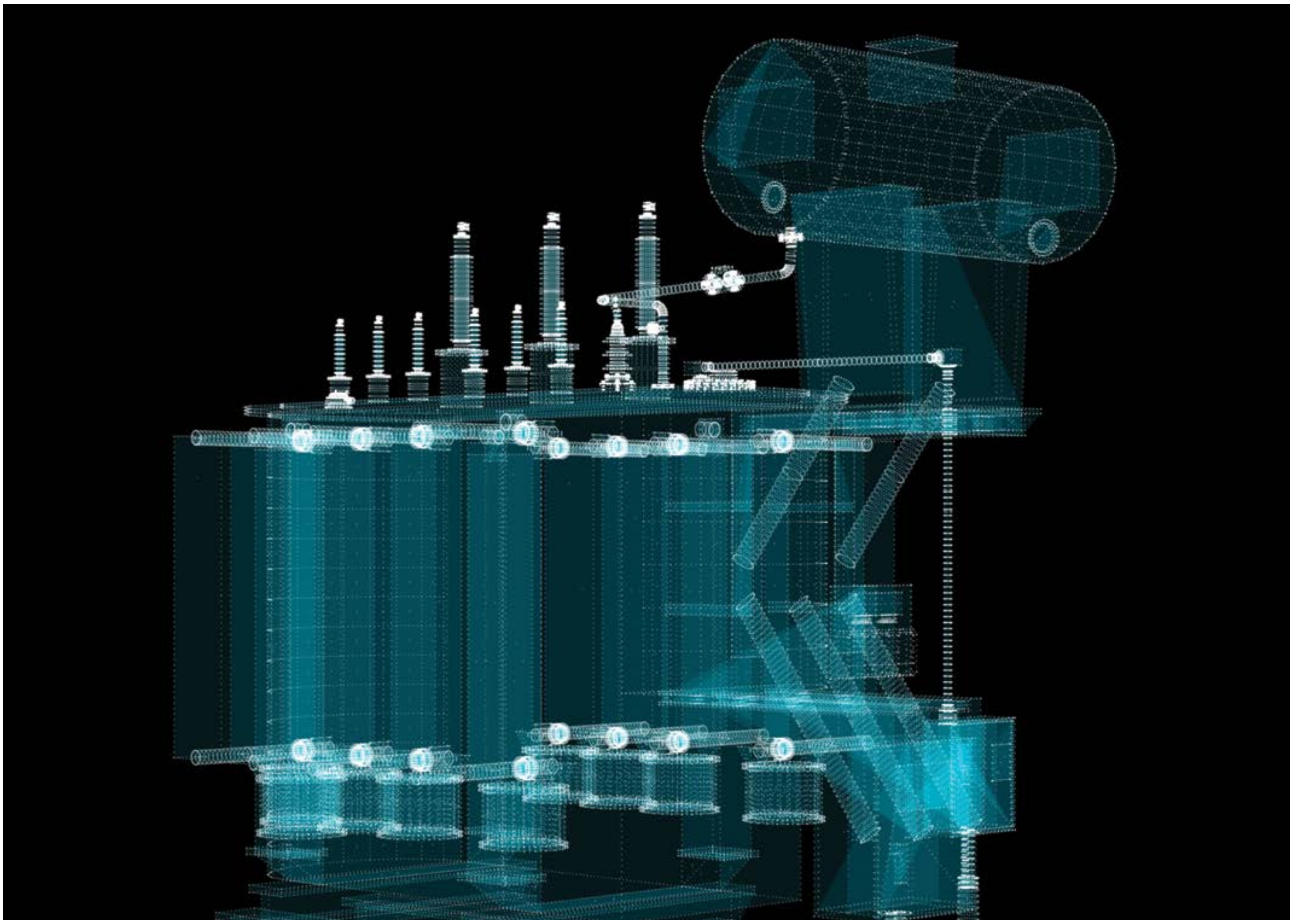


Figure 5. Concept of a different approach to computerized DGA diagnosis



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